Title: Elliptic Rydberg States as Direction Indicators

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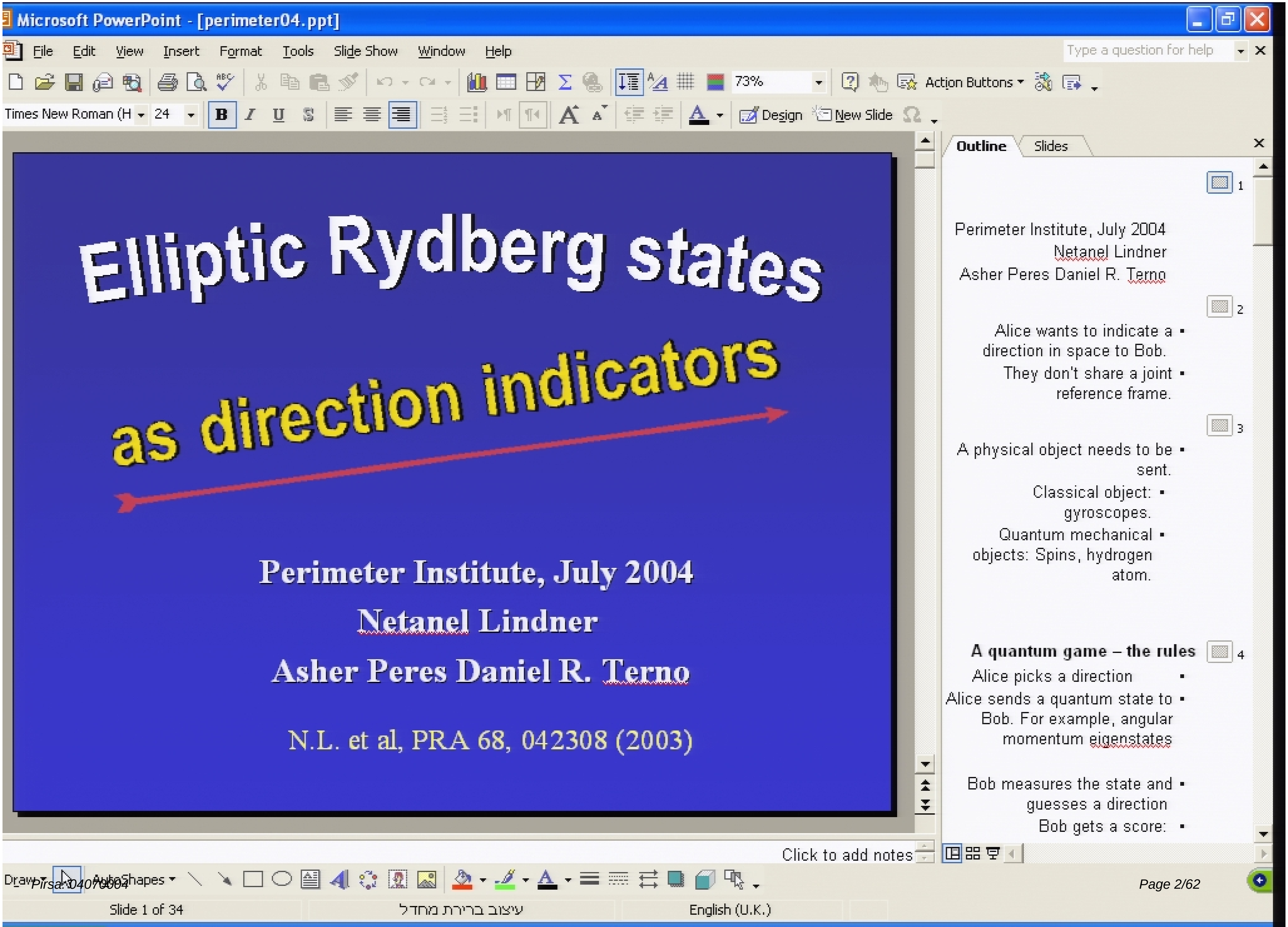
Abstract: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Elliptic Rydberg states
as direction indicators
Perimeter Institute, July 2004
Netanel Lindner
Asher Peres Daniel R. Terno
N.L. et al, PRA 68, 042308 (2003)
Outline
Slides
Perimeter Institute, July 2004
Netanel Lindner
Asher Peres Daniel R. Terno
Alice wants to indicate a direction in space to Bob.
They don't share a joint reference frame.
A physical object needs to be sent.
Classical object: gyroscopes.
Quantum mechanical objects: Spins, hydrogen atom.
A quantum game – the rules
Alice picks a direction
Alice sends a quantum state to Bob. For example, angular momentum eigenstates
Bob measures the state and guesses a direction
Bob gets a score:
Click to add notes
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English (U.K.)

Elliptic Rydberg states

as direction indicators

Perimeter Institute, July 2004

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N.L. et al, PRA 68, 042308 (2003)

- Alice wants to indicate a direction in space to Bob.

θ, φ

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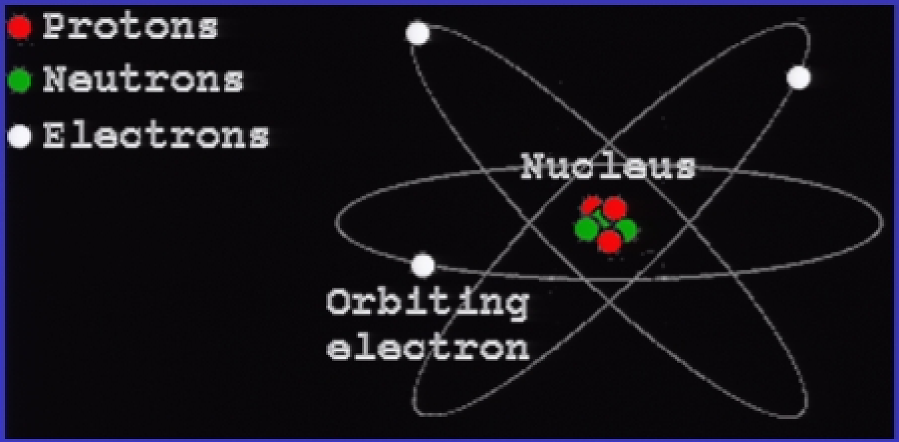
- They don't share a joint reference frame.

- **A physical object needs to be sent.**
  - Classical object: gyroscopes.
  - Quantum mechanical objects: Spins, hydrogen atom.



A quantum game – the rules

- Alice picks a direction $\hat{\mathbf{n}}_A$
- Alice sends a quantum state to Bob. For example, angular momentum eigenstates

$$\hat{\mathbf{n}}_A \cdot \mathbf{J}|\psi\rangle = j|\psi\rangle$$

- Bob measures the state and guesses a direction $\hat{\mathbf{n}}_B$
- Bob gets a score: $\dfrac{1+\hat{\mathbf{n}}_A \cdot \hat{\mathbf{n}}_B}{2} \equiv \cos^2(\omega/2)$

- **Objective:** Maximize fidelity $F = \langle \cos^2(\omega/2) \rangle$

Case study: Alice has two spins

$|\uparrow\uparrow\rangle$ $|\uparrow\downarrow\rangle$

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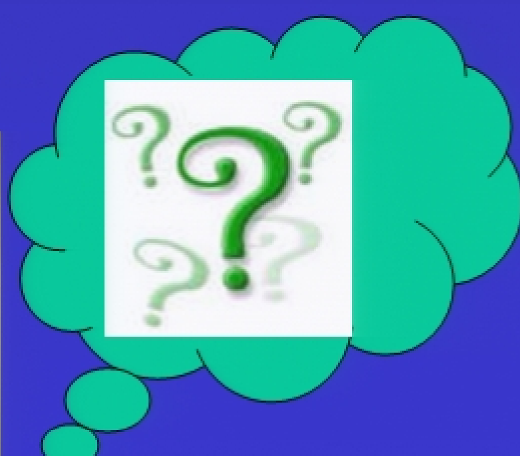
$F = 0.750$

$|\uparrow\downarrow\rangle$

$F = 0.785$



- **Objective:** Maximize fidelity $F = \langle \cos^2(\omega/2) \rangle$

Case study: Alice has two spins

$$|\uparrow\uparrow\rangle$$

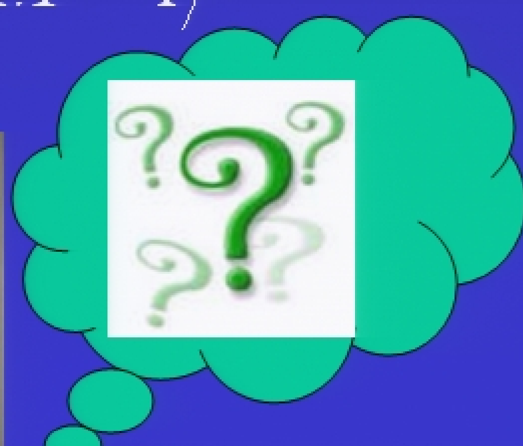
$$F = 0.750$$

$$= |J = 1, M = 1\rangle$$

$$|\uparrow\downarrow\rangle$$

$$F = 0.785$$

$$= \frac{1}{\sqrt{2}}|J = 0, M = 0\rangle + \frac{1}{\sqrt{2}}|J = 1, M = 0\rangle$$



N. Gisin and S. Popescu PRL **83** 432 (1999)

Aligning a Cartesian frame

- **Find the rotation that brings Bob's frame to Alice's.**
- **Same rules .**
- **Three directions:**

$$F = \sum_{k=1,3} \left\langle \cos^2(\omega_k/2) \right\rangle$$

Bob's measurment

- Bob's detectors have labels $\psi\theta\phi$ which indicate the unknown ***Euler angles*** relating his Cartesian axes to those used by Alice.
- The mathematical representation of his apparatus is a **POVM:**

$$\int d_{\psi\theta\phi} E_{\psi\theta\phi} = 1 \qquad d_{\psi\theta\phi} = \sin\theta d\theta d\psi d\phi / 8\pi^2$$

$$E_{\psi\theta\phi} = |\psi\theta\phi\rangle\langle\psi\theta\phi|$$

$$|B\rangle = \sum_{l=0}^{n-1} \sqrt{2l+1} \sum_{m=-l}^{l} b_{lm} |lm\rangle$$

$$\sum_{m=-l}^{l} |b_{lm}|^2 = 1$$

$$|\psi\theta\phi\rangle = U(\psi\theta\phi)|B\rangle$$

By Schur's lemma, this construction gives a resolution of identity,

Bob's measurment

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Alice

- Suppose Alice sends a hydrogen atom in the *n*th energy level.
- We wish to find feasible atomic state which would minimize the transmission error.
- Alice's signal, written in Alice's notation is

$$|A\rangle = \sum_{l=0}^{n-1} \sum_{m=-l}^{l} a_{lm} |lm\rangle.$$

- **Caution: $|A\rangle$ is in written in Alice's notation, $|B\rangle$ is written in Bob's.**

- **Define** the Euler angles $\alpha\beta\gamma$ that rotate Bob's Cartesian frame into his **estimate** of Alice's frame and then rotate back by the **true angles** from Alice's to Bob's frame.

$$U(\alpha\beta\gamma) = U(true)^{\dagger} U(\alpha\beta\gamma)$$

- $\alpha\beta\gamma$ indicate Bob's measurement error. The probability of that error is:

$$dP(\alpha\beta\gamma) = \left|\langle A|U(\alpha\beta\gamma)|B\rangle\right|^2 d_{\alpha\beta\gamma}.$$

Optimality

- One direction: A. Peres and P. Scudo PRL **86** (2001)

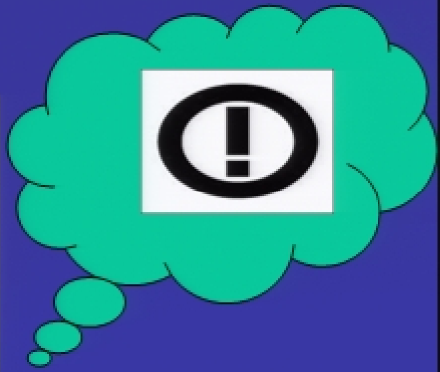
$$|A\rangle = \sum_{j=0,n-1} a_j |j0\rangle \qquad F = 1 - \frac{2.4}{(2n+1)^2}$$

- Reference frame: A. Peres and P. Scudo, PRL **87** (2001)
  Bagan et al, PRL **87** 257903 (2001)

$$|A\rangle = \sum_{j=0,n-1} a_j |jj\rangle \qquad F = 1 - \frac{1}{n}$$

$$b_{jm} = a_{jm}\left(\sum_n |a_{jn}|^2\right)^{-1/2}$$

Optimality



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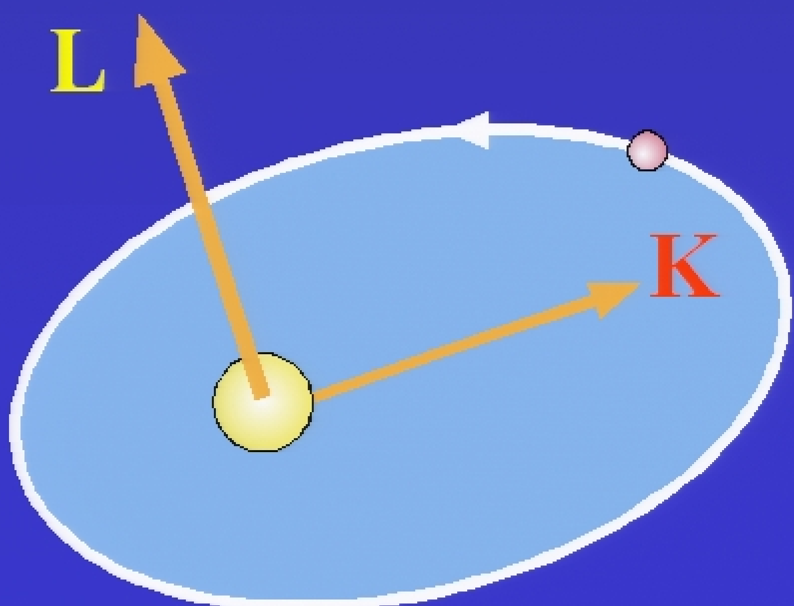
Classical Mechanics

- Vectorial constants of motion in a classical Keplerian orbit:
  - Angular momentum.
  - Laplace-Runge-Lenz vector.



$$\mathbf{L} \cdot \mathbf{K} = 0$$

Quantum elliptic states

Atomic states with the following properties:

- Eigenstates of the Hamiltonian.
- $|\psi|^2$ maximally localized on a classical elliptic trajectory. (elliptical "torus").
- minimal fluctuations on **L** and **K**, i.e.

  minimal $(\Delta \mathbf{L})^2 + (\Delta \mathbf{K})^2$.

The Laplace-Runge-Lenz (LRL) operator is defined by

$$\mathbf{K} = (-2H)^{-1/2}[(\mathbf{p}\times\mathbf{L} - \mathbf{L}\times\mathbf{p})/2 - \mathbf{r}/r]$$

where L is the orbital angular momentum, and H is the Hamiltonian.

L and **K** have the commutation relations of infinitesimal rotation generators in four dimensional Euclidian space:

$$\left[L_i, L_j\right] = i\varepsilon_{ijk}L_k$$

$$\left[L_i, K_j\right] = i\varepsilon_{ijk}K_k$$

$$\left[K_i, K_j\right] = i\varepsilon_{ijk}L_k.$$

L,K → Generators of SO(4) rotation group.

- As in a classical Keplerian orbit: $\mathbf{L}\cdot\mathbf{K}=\mathbf{K}\cdot\mathbf{L}=0.$

- For energy eigenstates: $\mathbf{L}^2+\mathbf{K}^2=1-1/2H=n^2-1.$

- Define: $\mathbf{J}_1=(\mathbf{L}-\mathbf{K})/2, \quad \mathbf{J}_2=(\mathbf{L}+\mathbf{K})/2.$

- $\mathbf{J}_1$, $\mathbf{J}_2$ have the commutation relations of two **independent** three dimensional angular momentum operators.

$$\mathrm{SO}(4)=\mathrm{SO}(3)\otimes\mathrm{SO}(3)$$

- For energy eigenstates: $\mathbf{J}_1^2=\mathbf{J}_2^2=(n^2-1)/4.$

Coherent States of SO(3)

Coherent states of 3D angular momentum obey:

$$\mathbf{u}\cdot\mathbf{J}\left|J,\mathbf{u}\right\rangle = j\left|J,\mathbf{u}\right\rangle$$

These states have **minimal dispersion:** $\Delta\mathbf{J} = \sqrt{\left\langle \mathbf{J}^2\right\rangle - \left\langle \mathbf{J}\right\rangle^2} = \sqrt{j}.$

Coherent states of SO(3) are obtained by a rotation of a fiducial coherent state, which is an eigenstate of J_z

$$\left|J,\mathbf{u}(\theta,\phi)\right\rangle = e^{-iL_z\phi}e^{-iL_z\theta}\left|jj\right\rangle.$$

Quantum elliptic states = coherent states of SO(4)

- SO(4) coherent states are obtained as a direct product of two SO(3) subgroups coherent states

$$|n,\mathbf{u}_1\mathbf{u}_2\rangle = |J_1,\mathbf{u}_1\rangle \otimes |J_2,\mathbf{u}_2\rangle, \qquad j_1 = j_2 = (n-1)/2.$$

- For these states, the dispersion of L^2+K^2 is minimal:

$$(\Delta \mathbf{L})^2 + (\Delta \mathbf{K})^2 = (\Delta \mathbf{J}_1)^2 + (\Delta \mathbf{J}_2)^2 = 2(n-1).$$

Corresponding classical orbit

Define the following unit vectors:

$$\mathbf{l} = \frac{\mathbf{u}_1 + \mathbf{u}_2}{|\mathbf{u}_1 + \mathbf{u}_2|}, \quad \mathbf{k} = \frac{\mathbf{u}_1 - \mathbf{u}_2}{|\mathbf{u}_1 - \mathbf{u}_2|}, \quad \mathbf{w} = \mathbf{k} \times \mathbf{l}.$$

The expectation values of the components of **K** and **L** along the directions of **k,** $\mathbf{l}$ and **w** are

$$\langle K_k \rangle = (n-1)\sin\zeta,$$ where $\langle K_k \rangle = \mathbf{k}\cdot\mathbf{K}$, etc.

$$\langle L_{\mathsf{l}} \rangle = (n-1)\cos\zeta.$$

ζ = Half the angle between $\mathbf{u}_1$ and $\mathbf{u}_2$

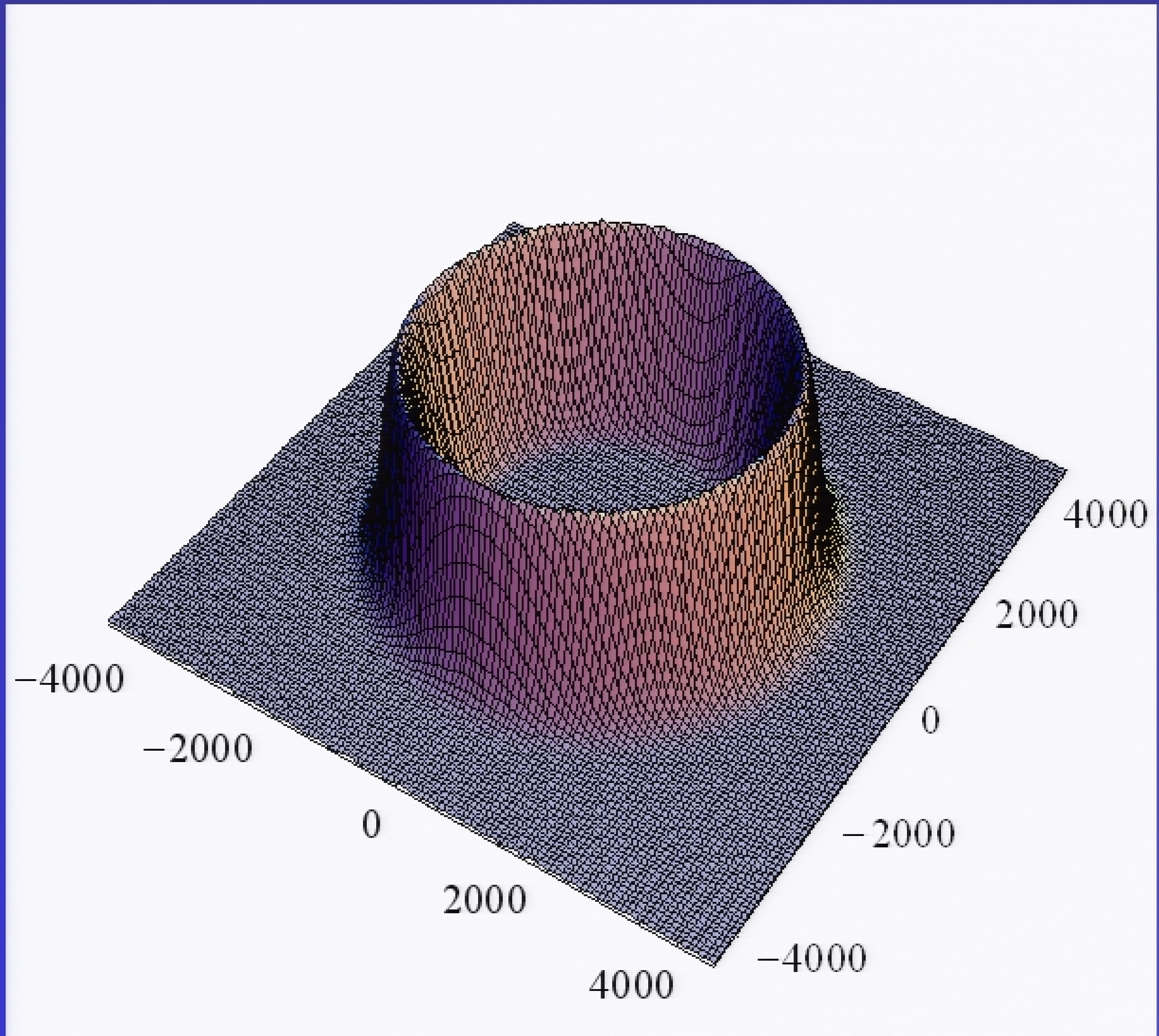
- In the perpendicular directions the expectation values vanish:

$$\langle K_{\mathbf{l}} \rangle = \langle L_k \rangle = \langle K_w \rangle = \langle L_w \rangle = 0.$$

- The coherent state $|n, \mathbf{u}_1 \mathbf{u}_2\rangle$ corresponds to a classical orbit in the **kw** plane with
  - major axis in the **k** direction,
  - angular momentum in the **l** direction,
  - eccentricity $e = \sin \zeta$.

Circular state, *xy*-plane

$|\psi|^2$ for $n=50$, $e=0$, l=z



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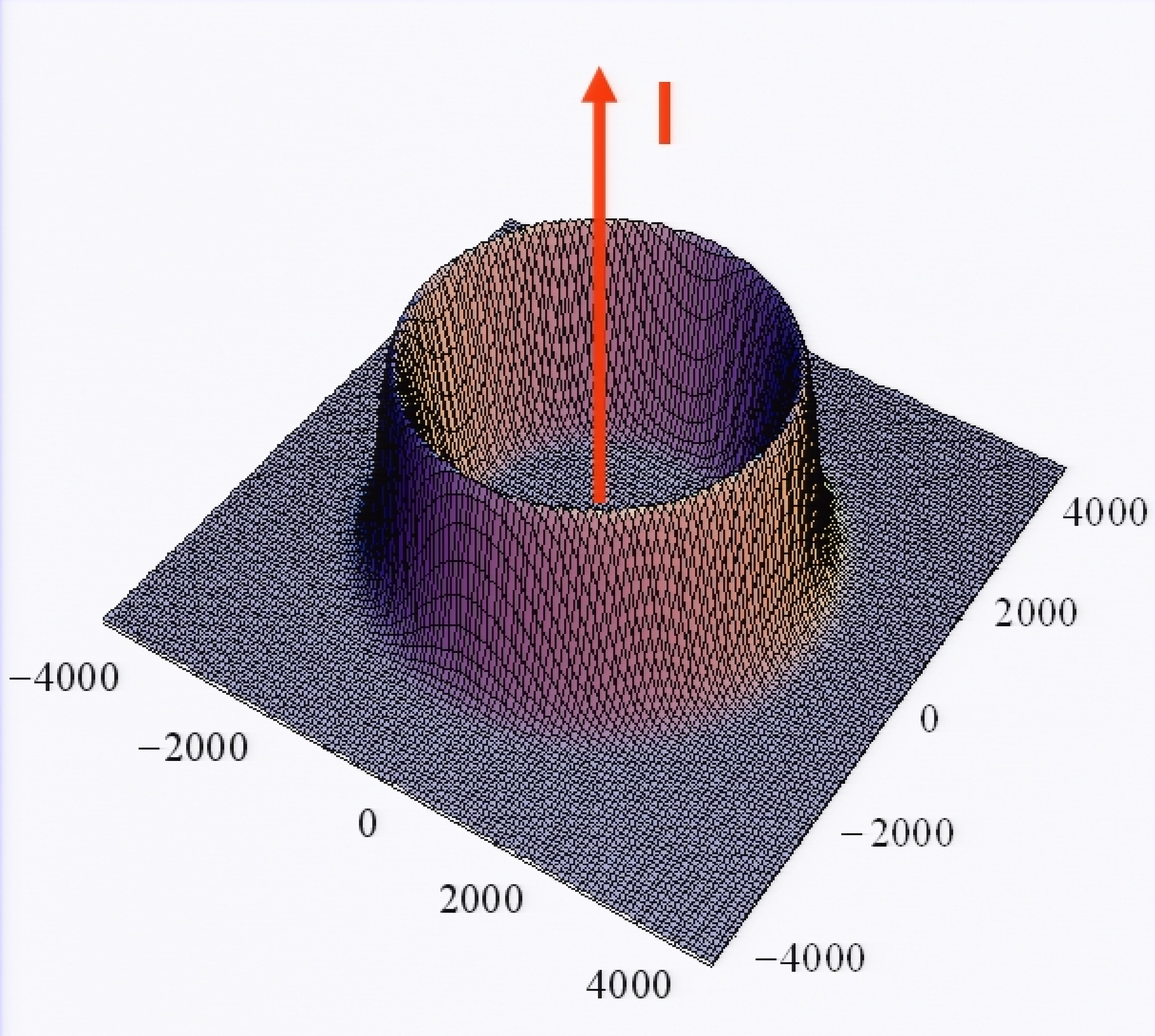
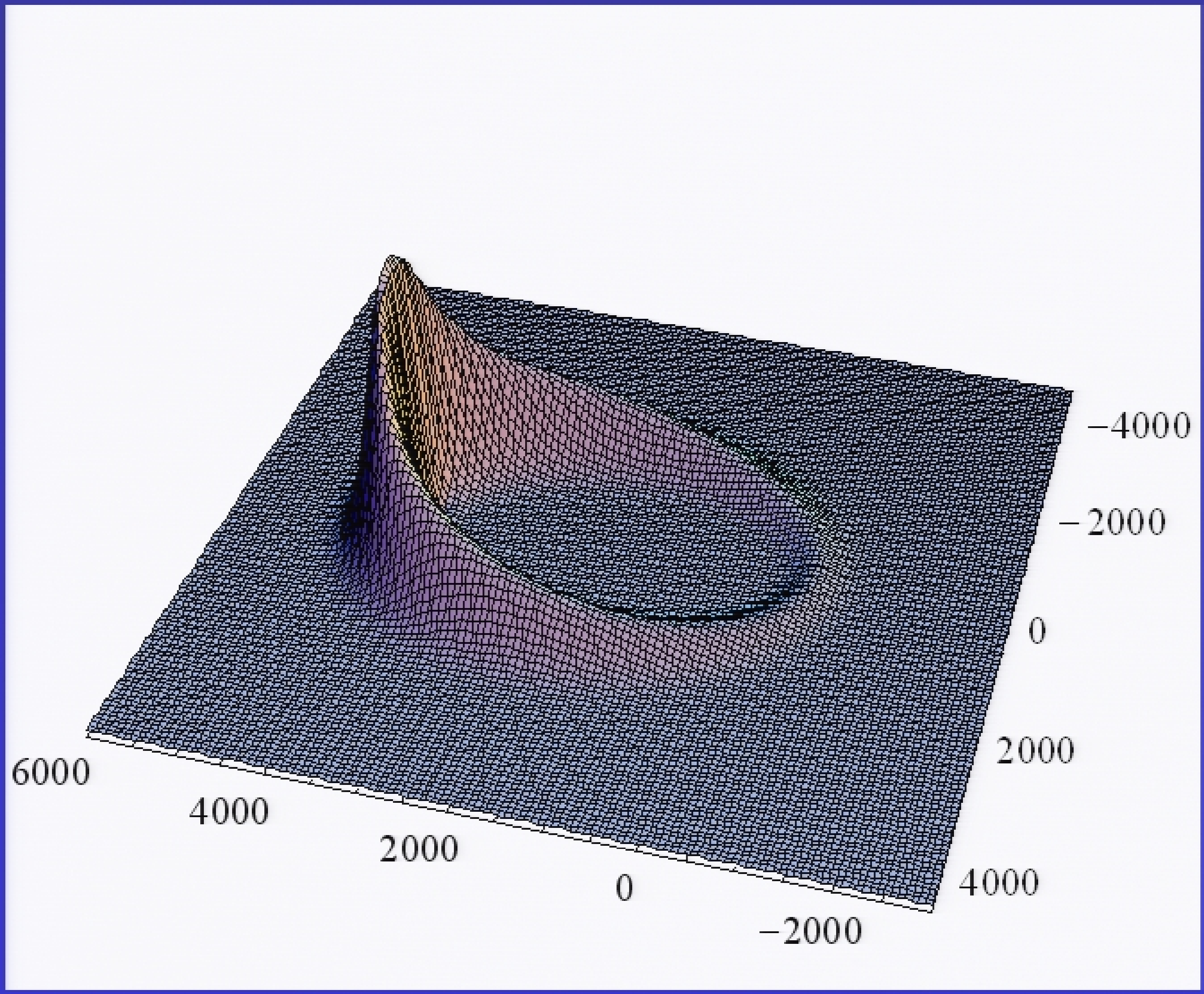


Generic elliptic state, *xy*-plane

$|\psi|^2$ for n=50, e=**0.7**, **k=x**, **l=z**



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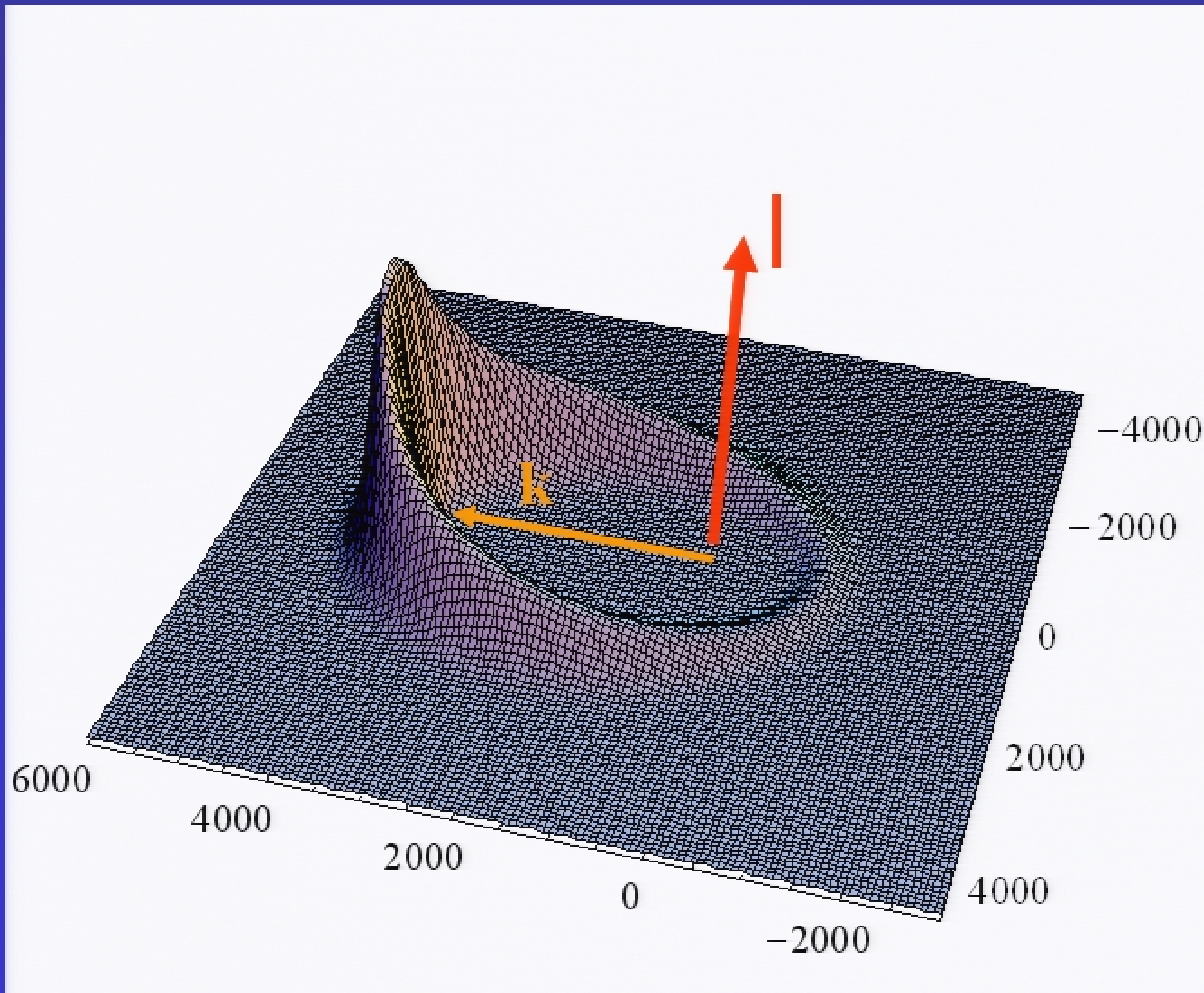

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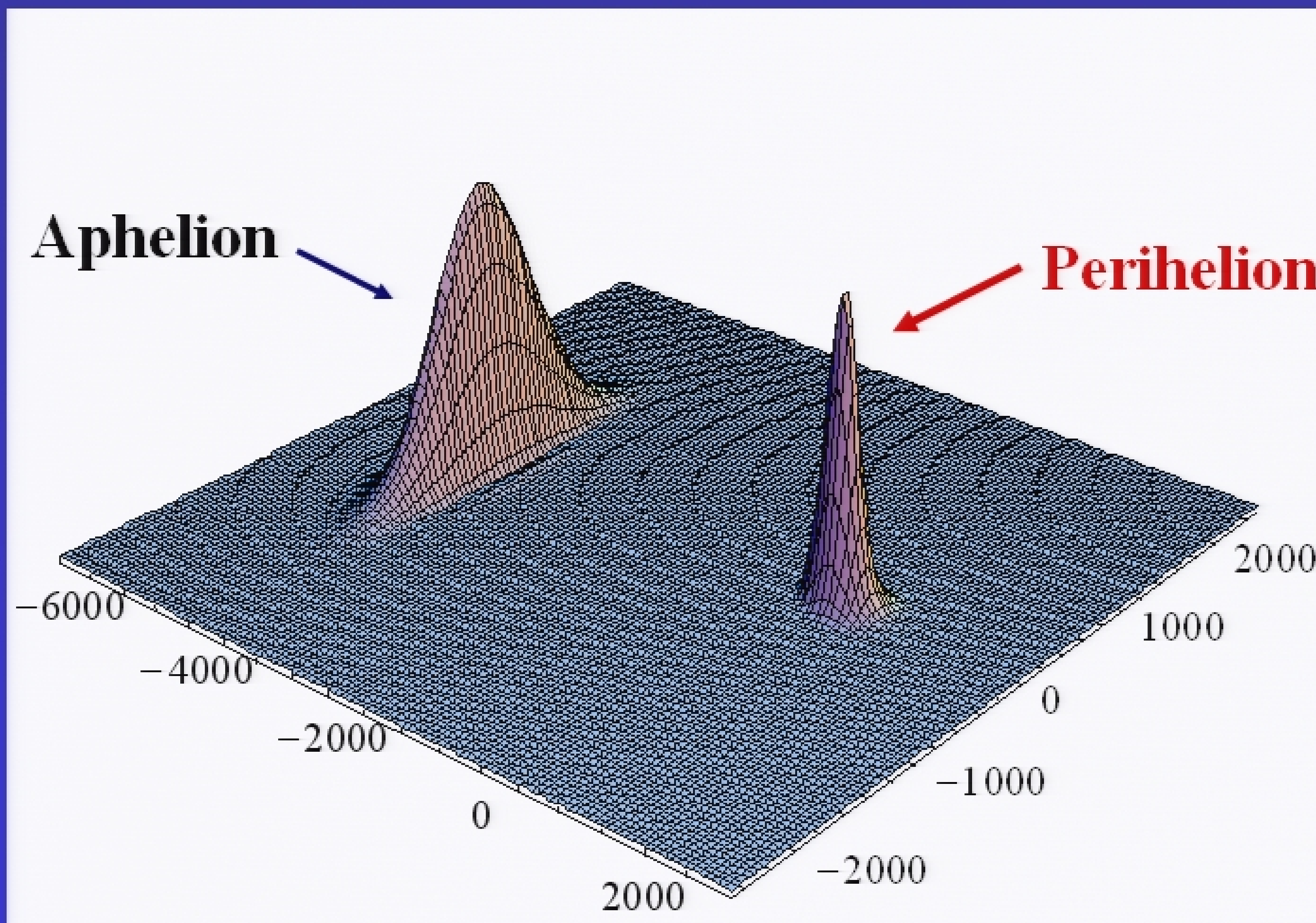

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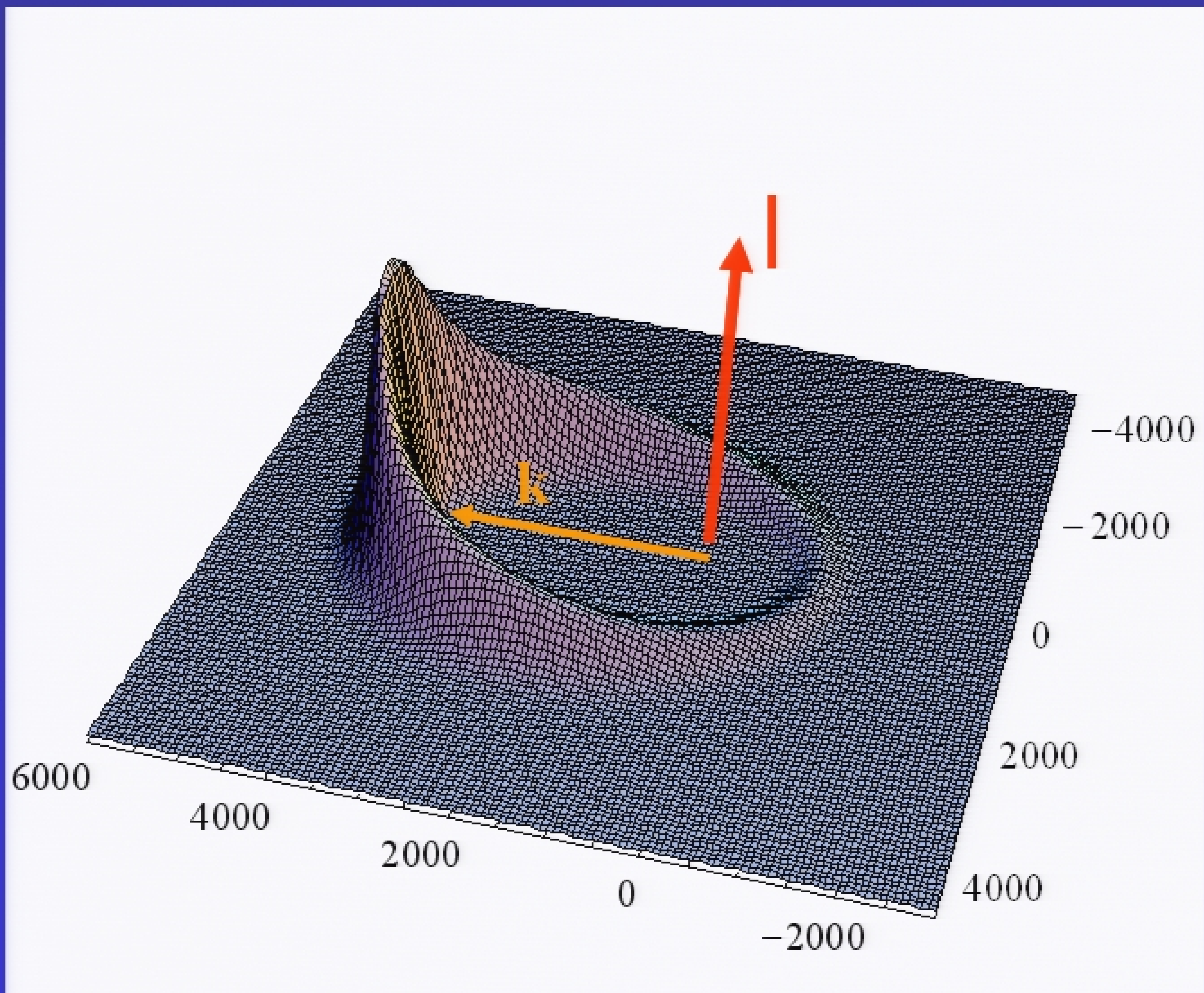

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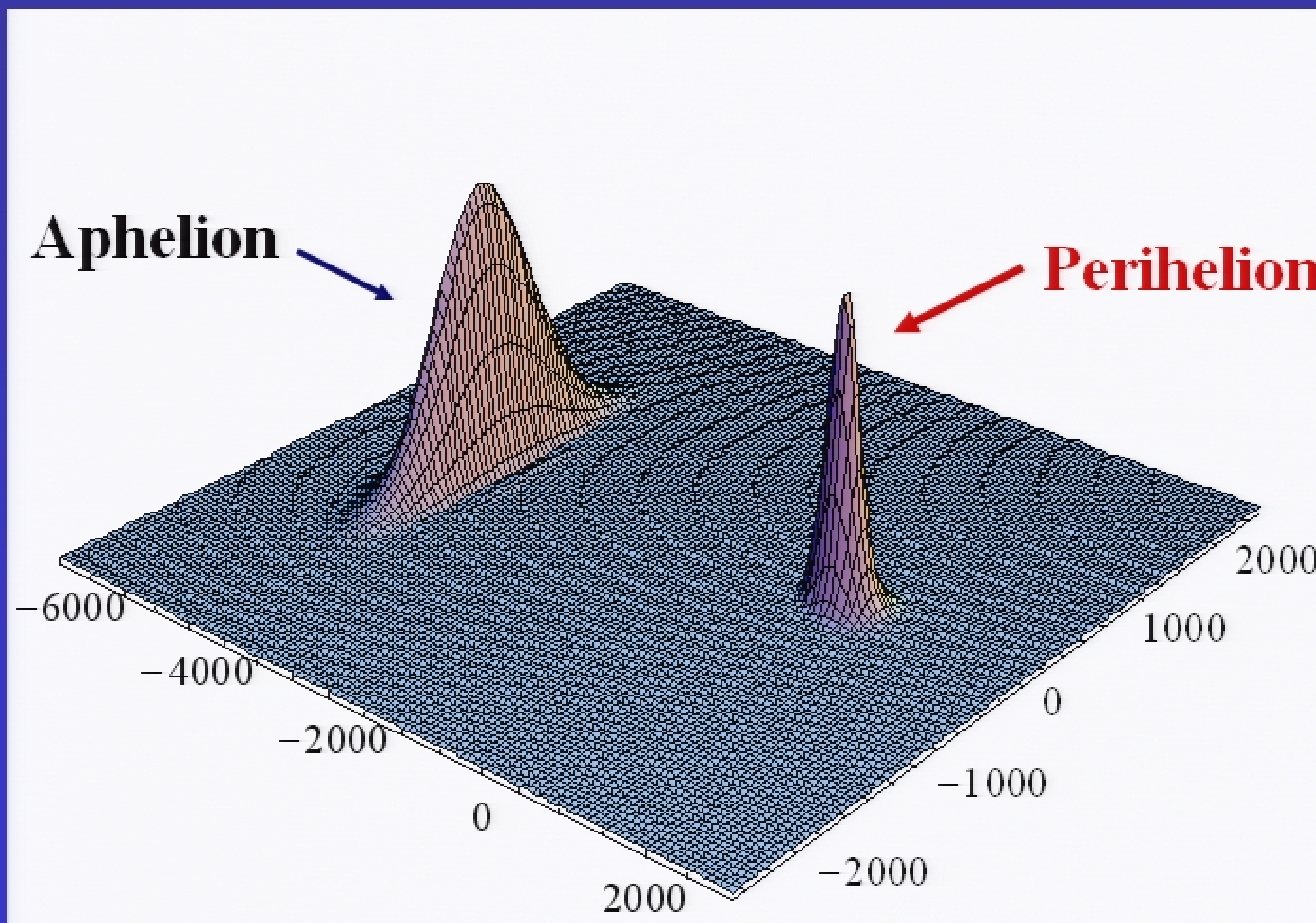
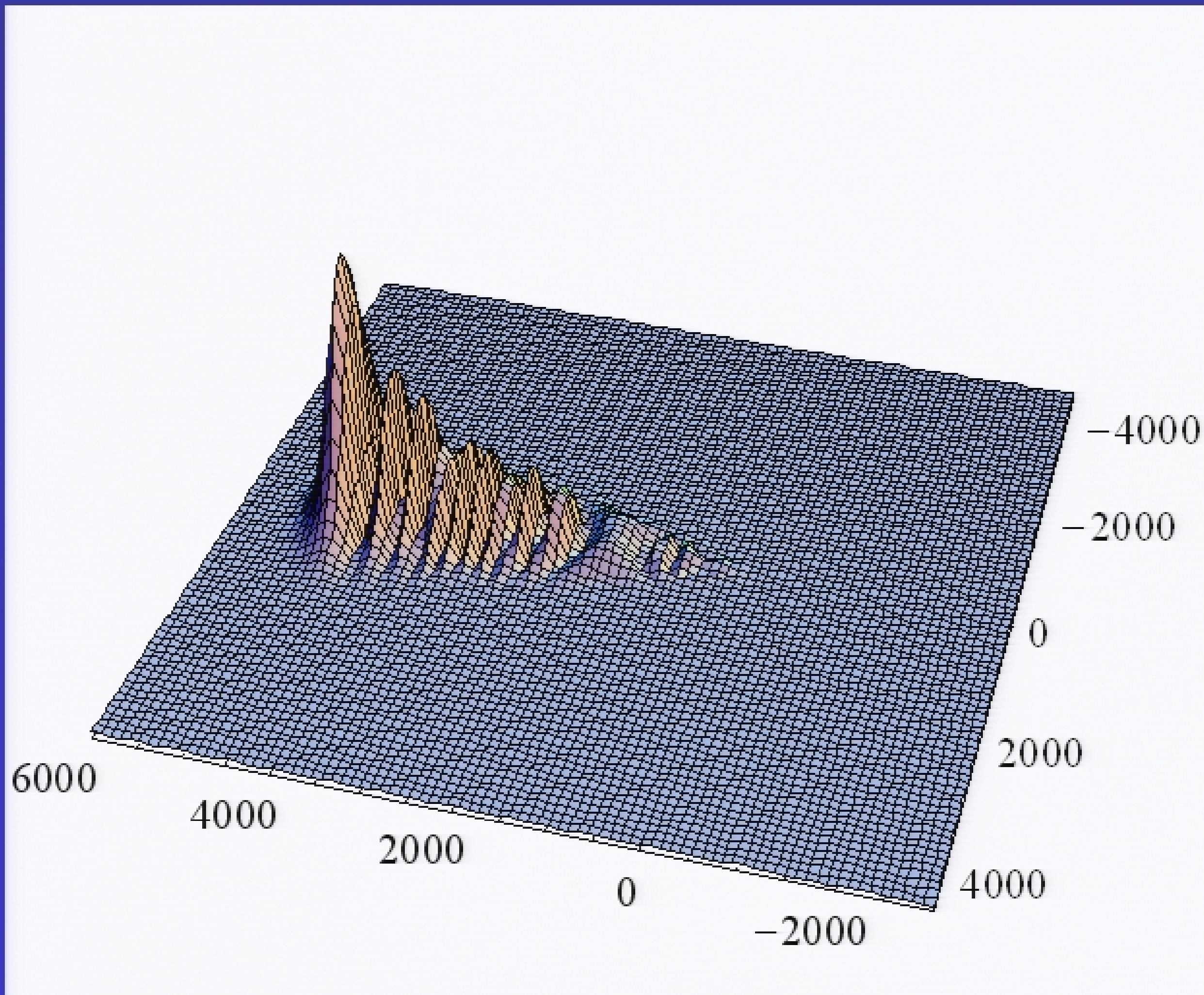


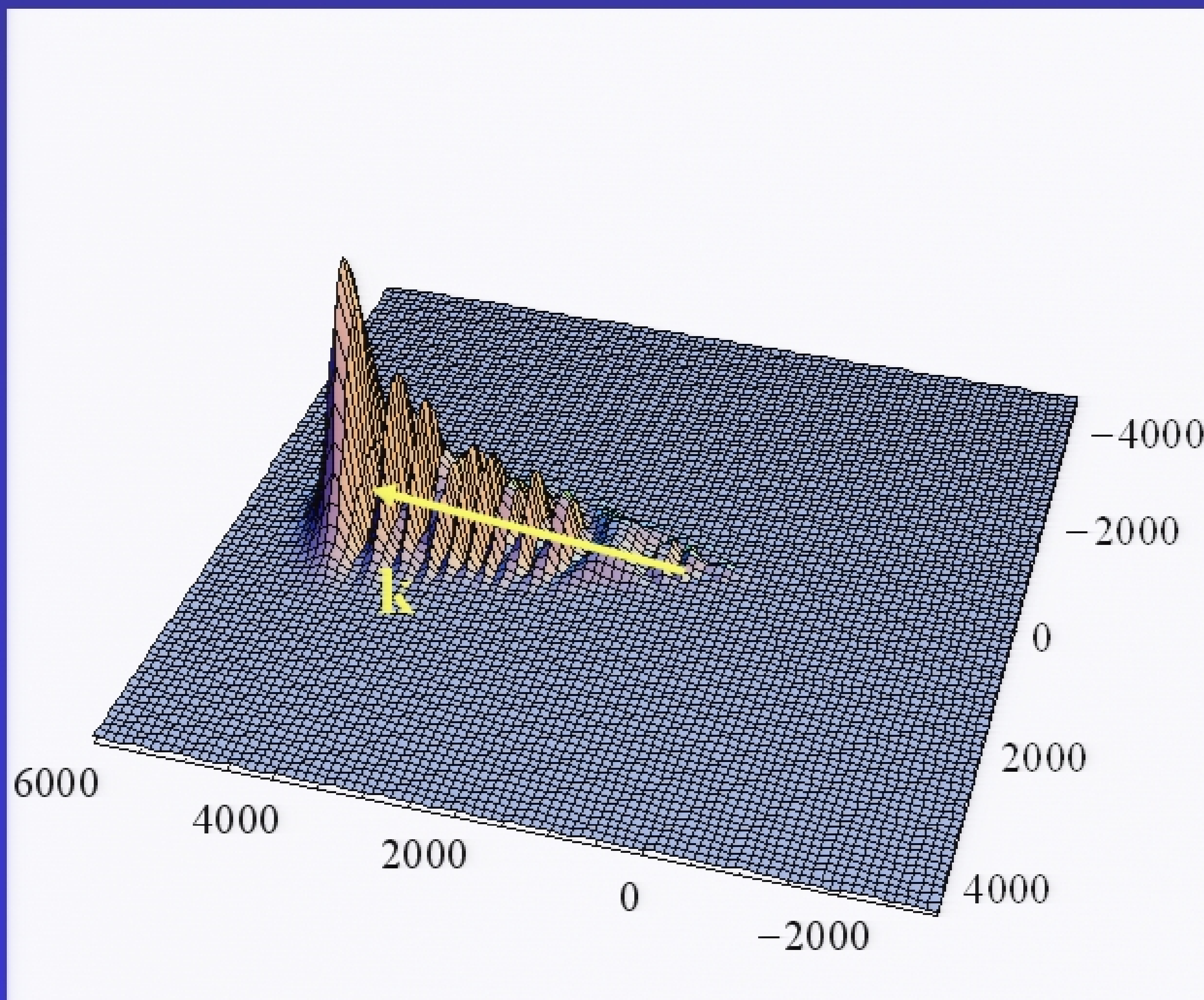
Extreme Stark state, *xy*-plane

$|\psi|^2$ for e=1, k=x



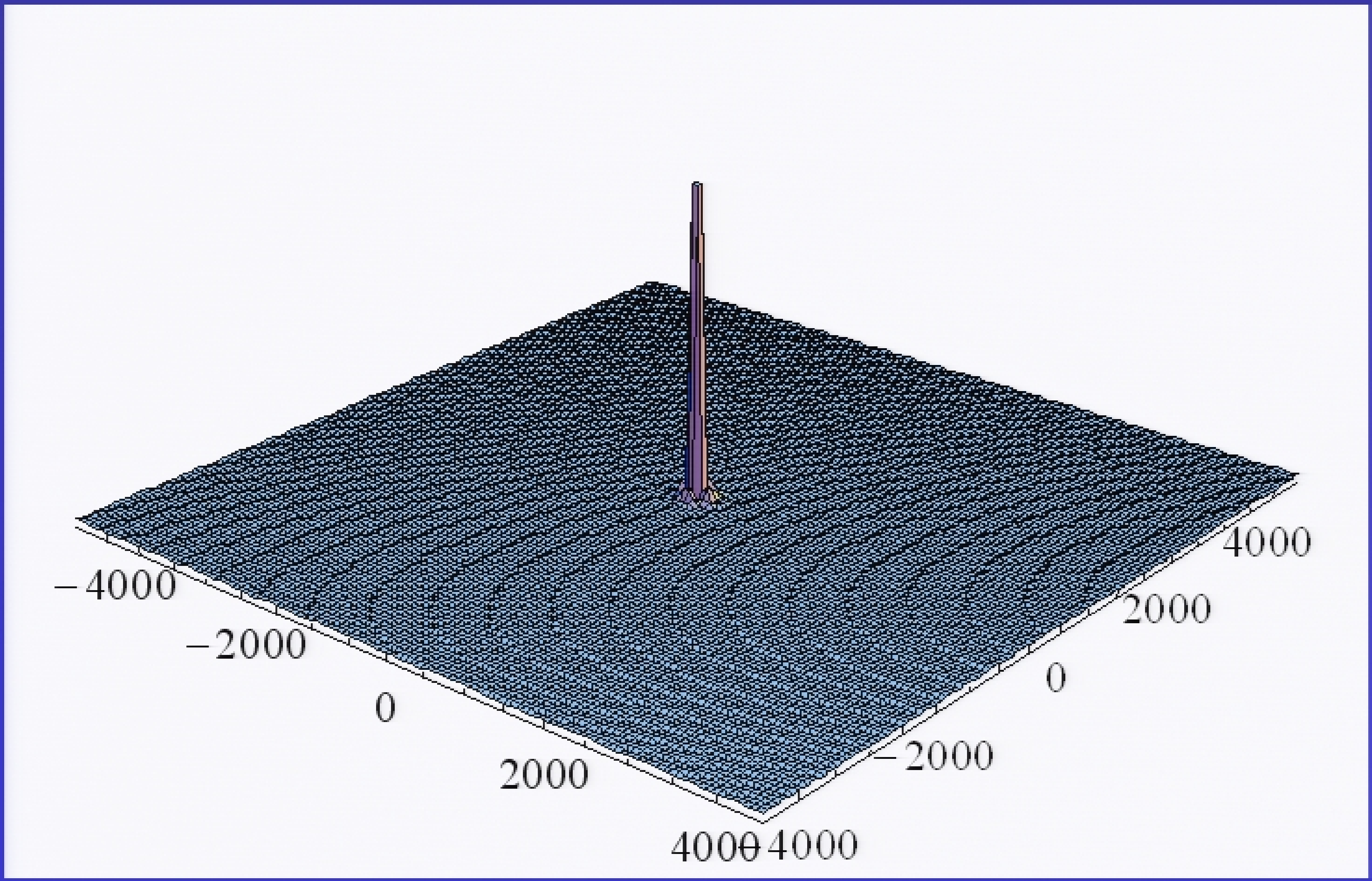
Extreme Stark state, *xy*-plane

$|\psi|^2$ for e=1, k=x



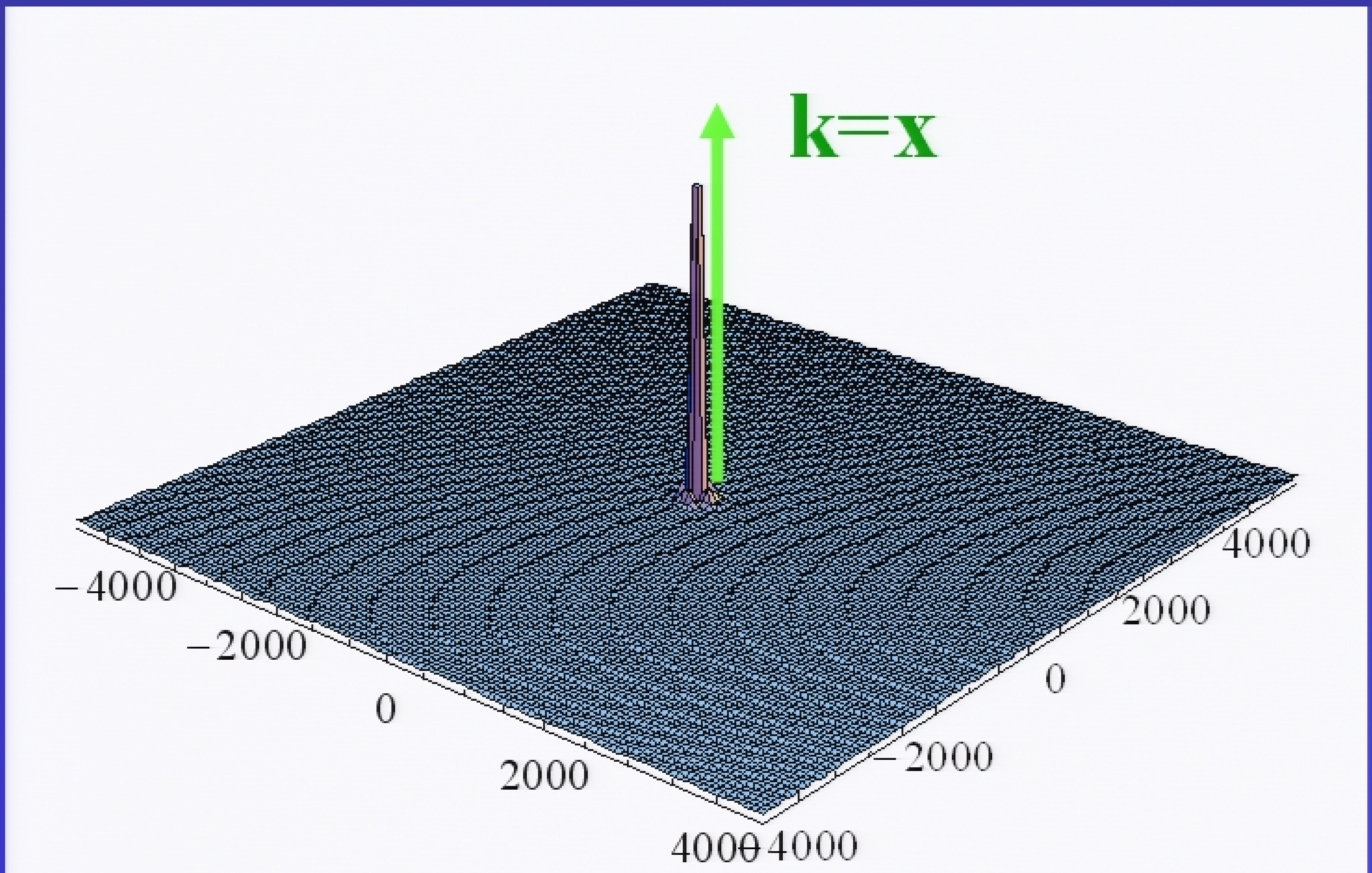
Extreme Stark state, *zy*-plane

$|\psi|^2$ for n=50, e=1, **k**=**x**



Extreme Stark state, *zy*-plane

$|\psi|^2$ for n=50, e=1, **k=x**



Transmission of One Direction

- Taking the transmitted direction to be Alice's z-axis

$$\langle \cos\omega_z \rangle = \int d_{\alpha\beta\gamma} \left|\langle A | U(\alpha\beta\gamma) | B \rangle\right|^2 \cos\beta.$$

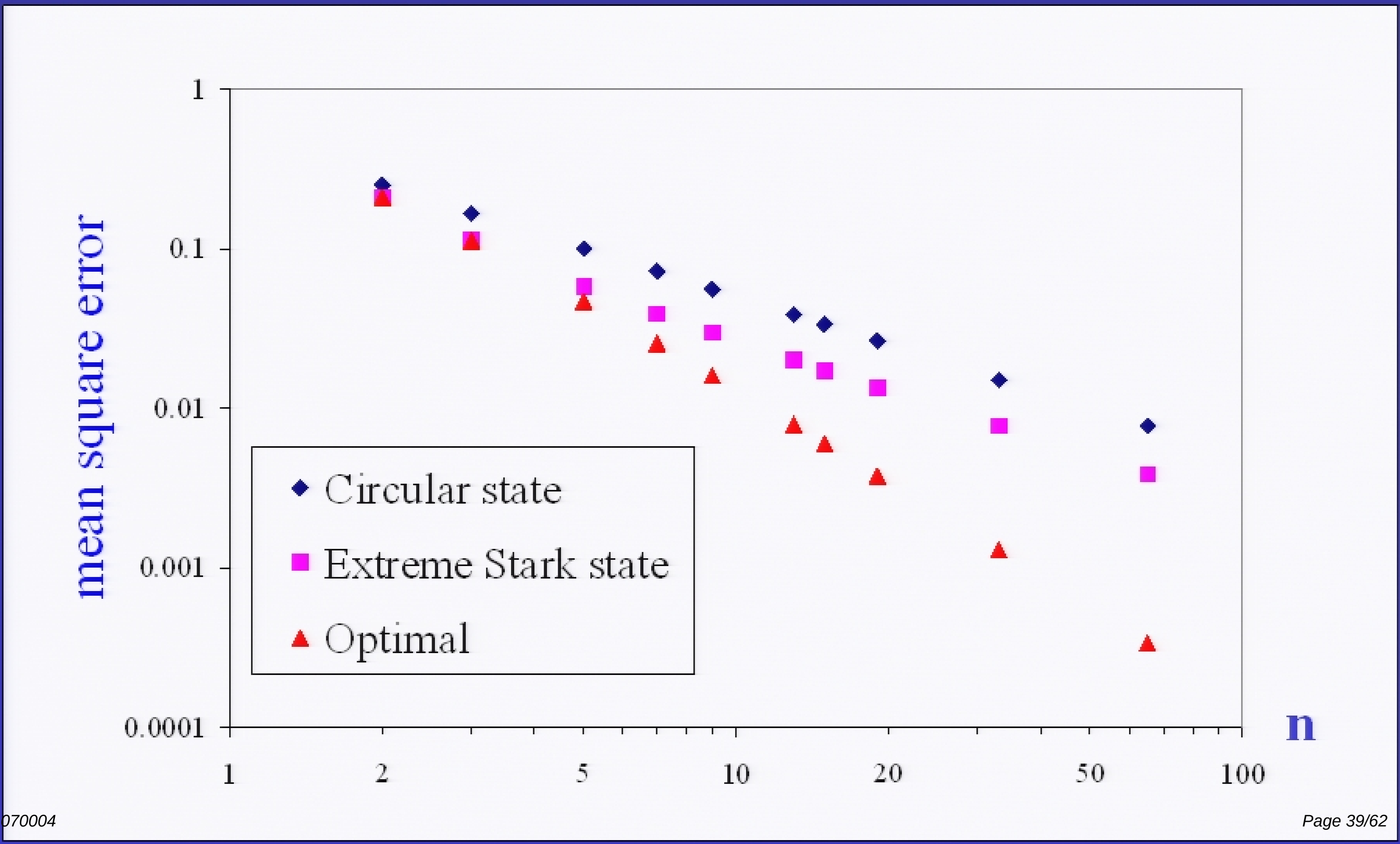
- Consider the following cases:
  - Circular State: $e = 0$, $\mathbf{l} = \mathbf{z}$, $\langle \mathbf{K} \rangle = 0$

    $$|A\rangle = |ll\rangle = |jj\rangle \otimes |jj\rangle$$

  - Extreme Stark State: $e = 1$, $\mathbf{k} = \mathbf{z}$, $\langle \mathbf{L} \rangle = 0$

    $$|A\rangle = |j,-j\rangle \otimes |jj\rangle$$

Comparison of the mean square error *1-F* to the optimal one



Transmission of two directions

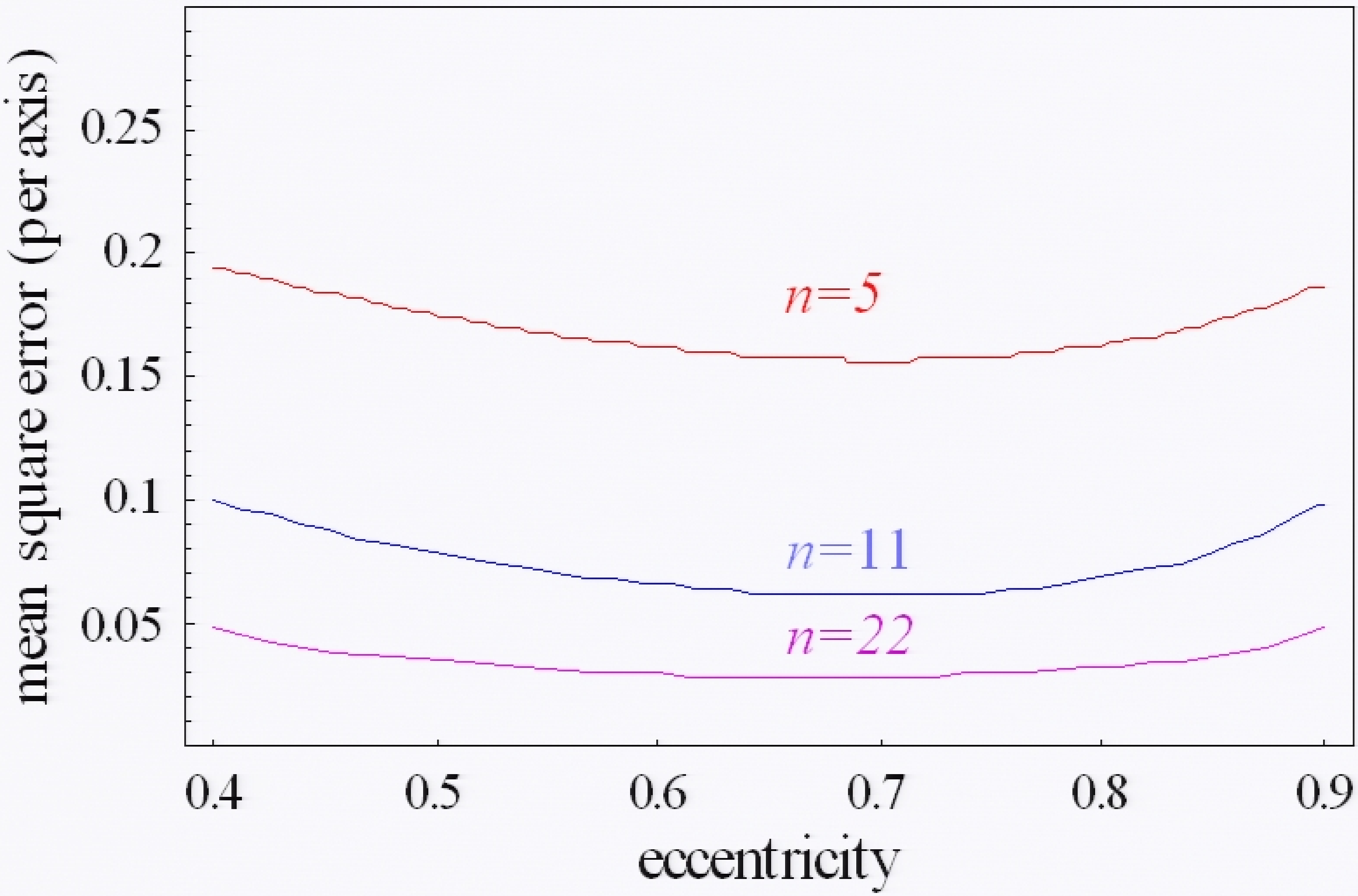
- We choose for Alice an elliptic state with **k**=**x**, **l** =**y**, and eccentricity $0<e<1$. The optimal eccentricity should be

$$\frac{\Delta K_\perp}{\langle K_k \rangle} = \frac{\Delta L_\perp}{\langle L_l \rangle} \Rightarrow e \approx 1/\sqrt{2}.$$

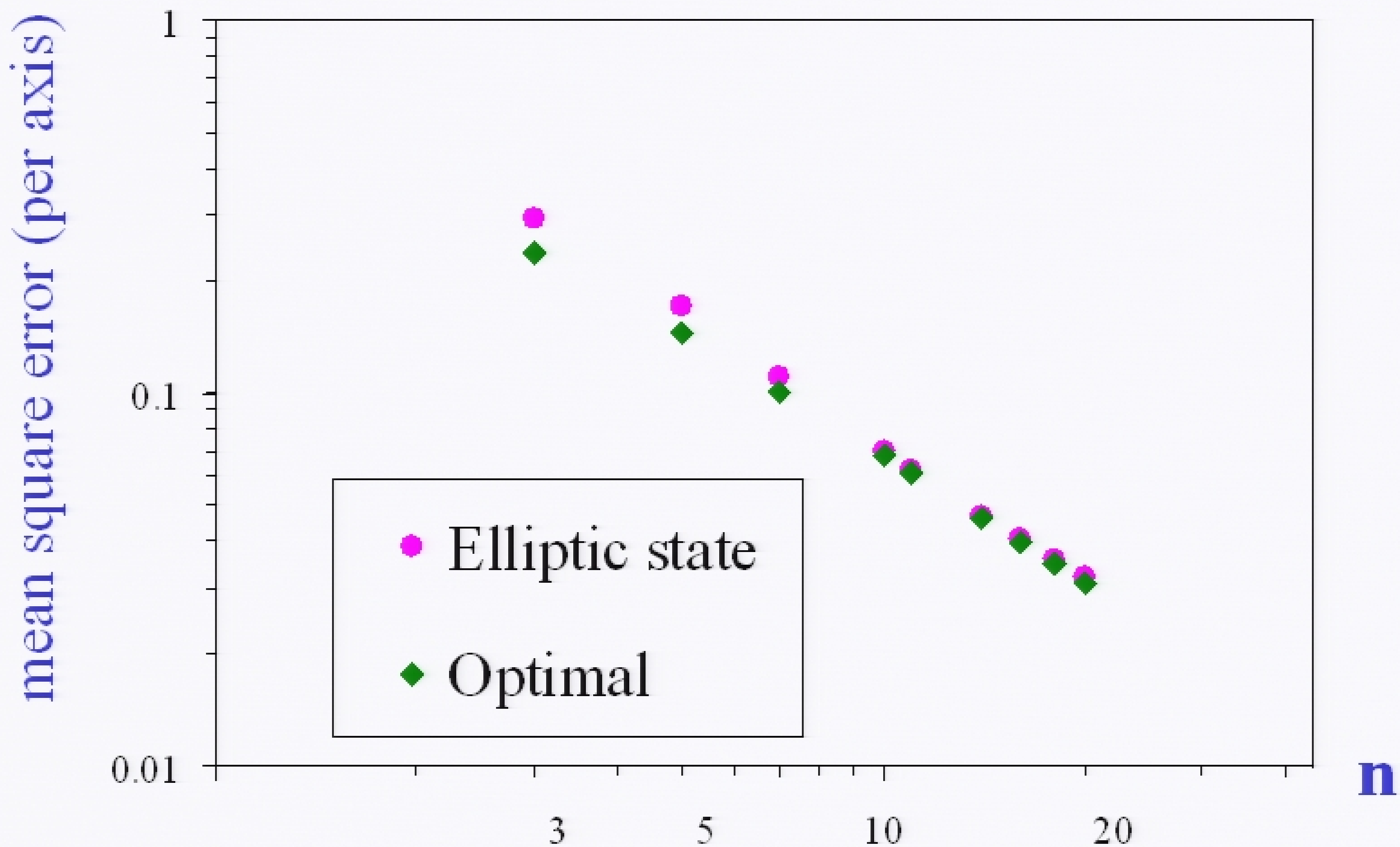
- To calculate the fidelity for the transmission of the x and y axes we need to calculate

$$\langle \cos\omega_x + \cos\omega_y \rangle = \langle (1+\cos\beta)(\cos\alpha + \cos\gamma) \rangle.$$

Mean square error vs. eccentricity for n=5, n=11, n=22

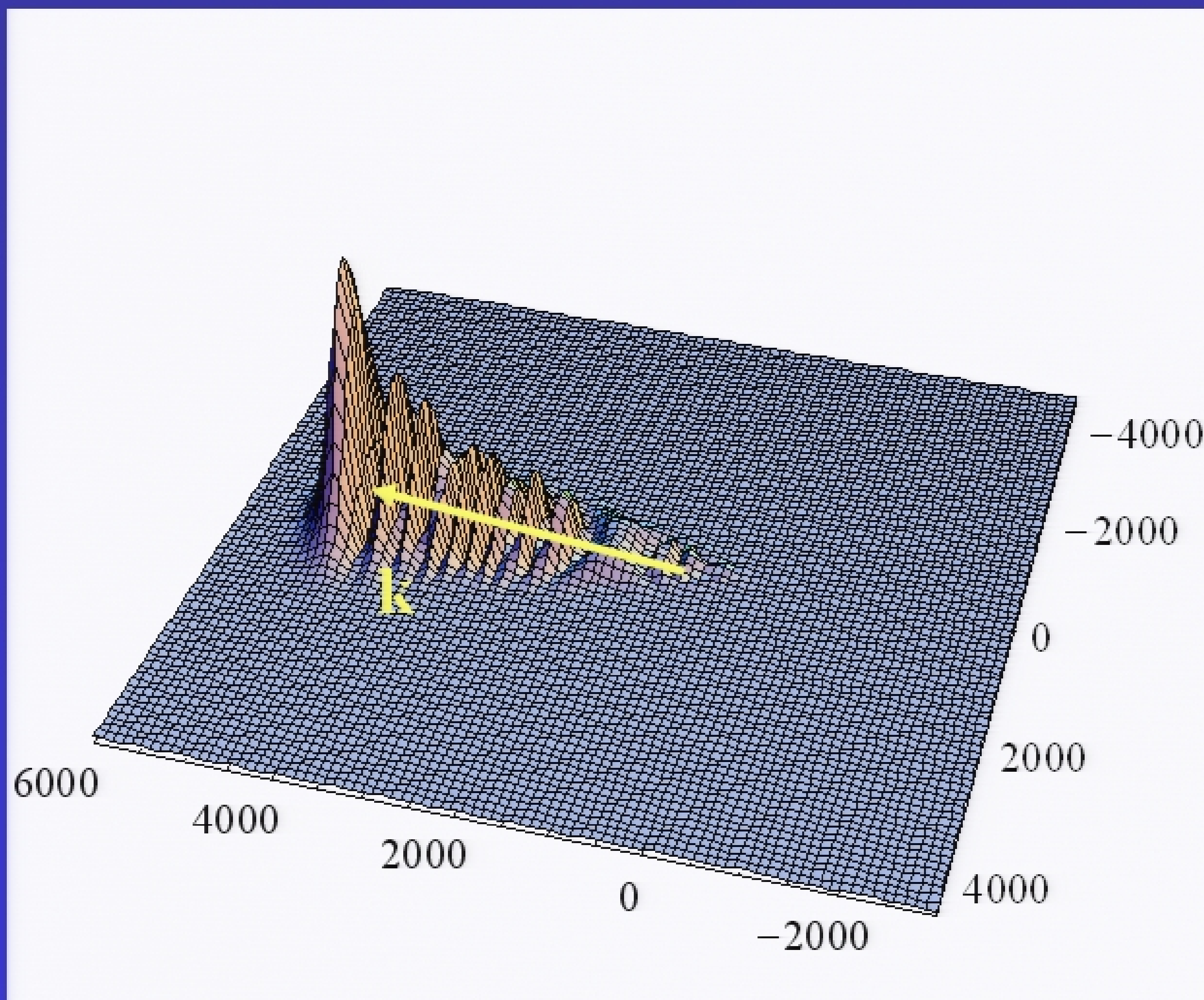


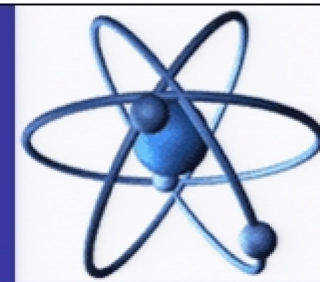
Comparison with the optimal transmission



Extreme Stark state, *xy*-plane

$|\psi|^2$ for e=1, k=x





The experimental situation

- Elliptic Rydberg states can be produced by exiting atoms in external orthogonal electric and magnetic field. J.C. Day et al, PRL. 72 (1994

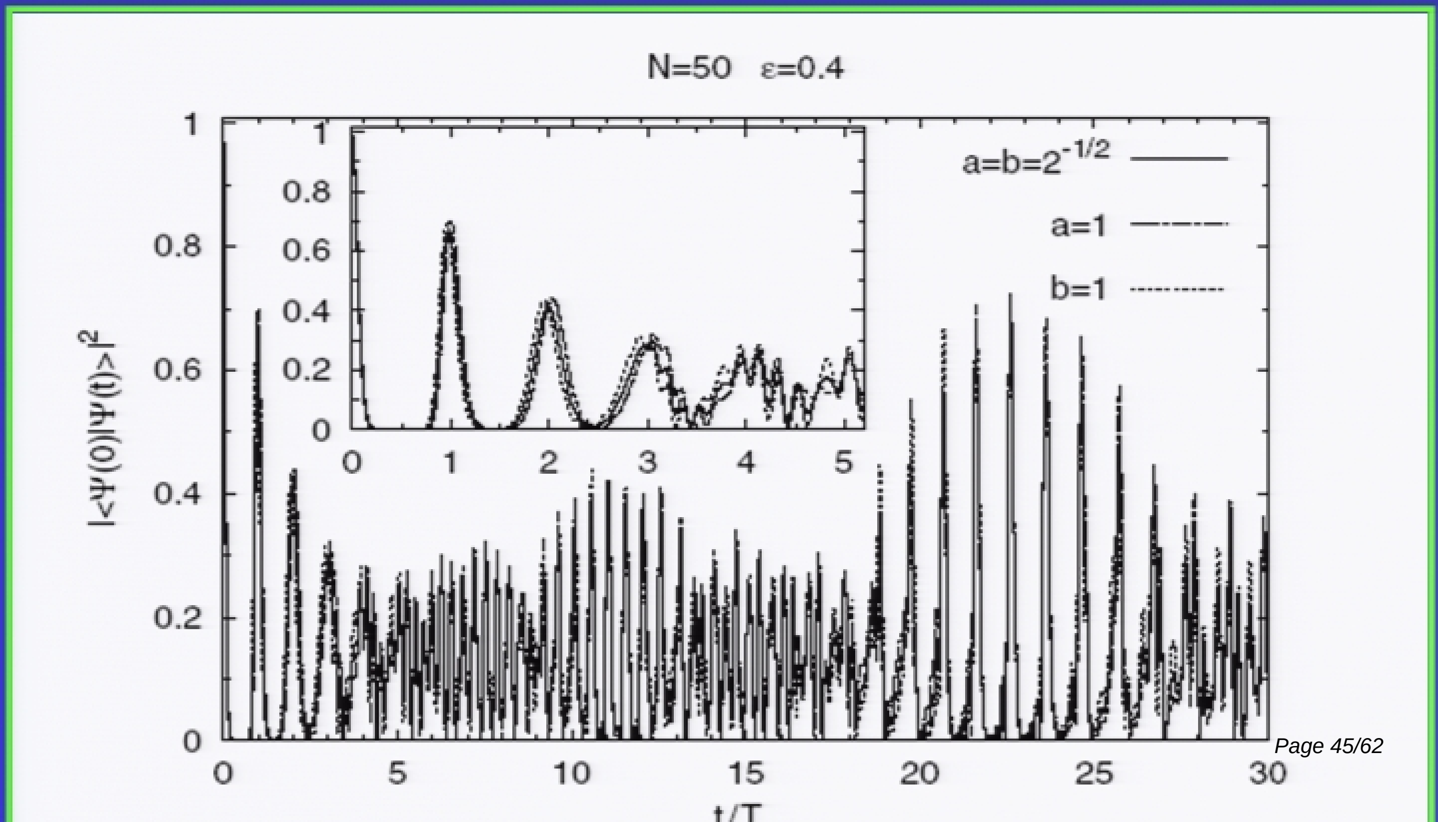
- Relativistic effects:

Energy depends on l, causes precession of the elliptic state. P. Rozmej et al, J. Phys A. 35 (2002)

$$E_{nlj} = E - \frac{Z^4\alpha^2}{2n^3(l+s+1/2)} \qquad j = l + s$$

$$T_p = \frac{2\pi}{\left\langle \frac{dE_{nlj}}{dl} \right\rangle} \qquad T_p = \frac{4\pi n^3\left[(n-1)\cos\zeta\right]^2}{Z^4\alpha^2}$$

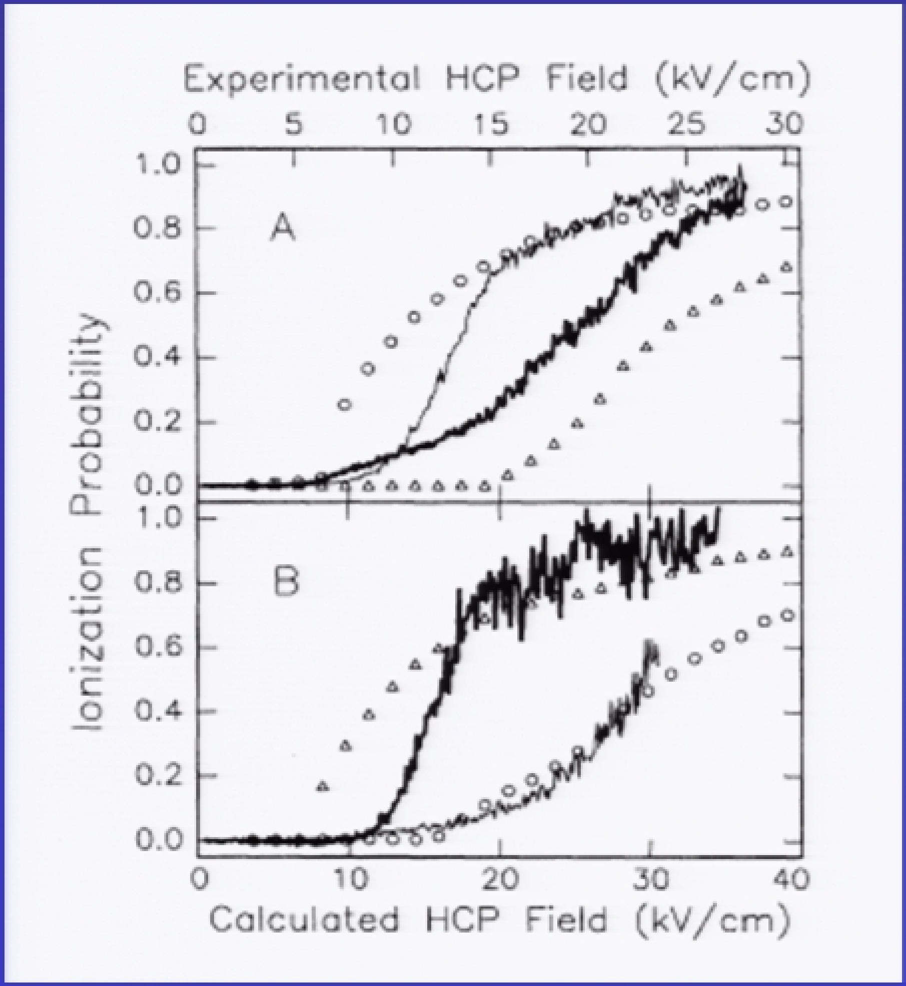
P. Rozmej et al, J. Phys. A **35,** 7803 (2002)



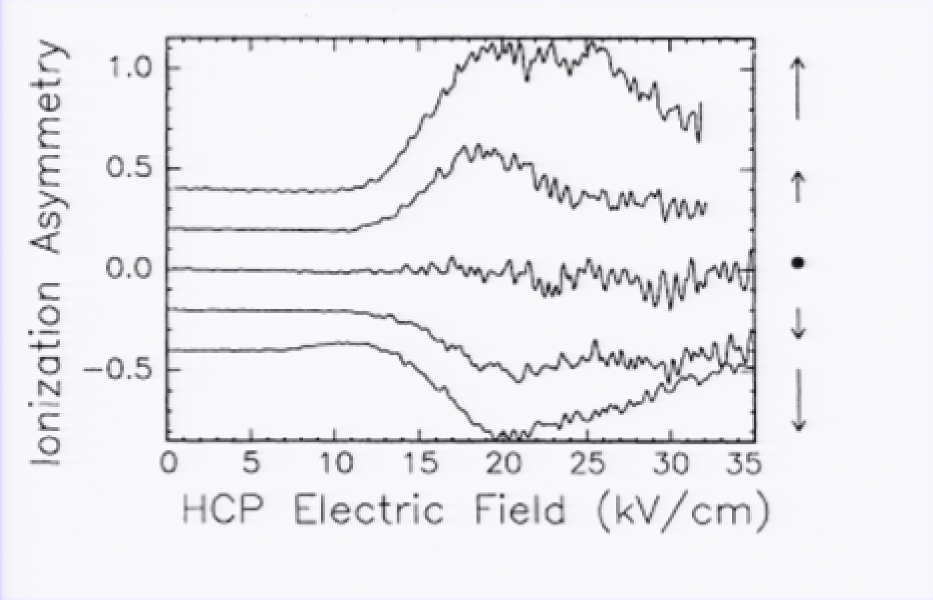
Characteristic Time Scales

- For Z=1 : $T_p \approx 1.4 \times 10^{-3}$ sec
- Spontaneous decay: $\frac{T_{n,l}^{rad}}{T_p} = \frac{3}{8\pi\alpha} \approx 16.3$

Probing the orientation of Rydberg states by an ionization pulse



Jones et al, **PRA** 51 2687 (1995)



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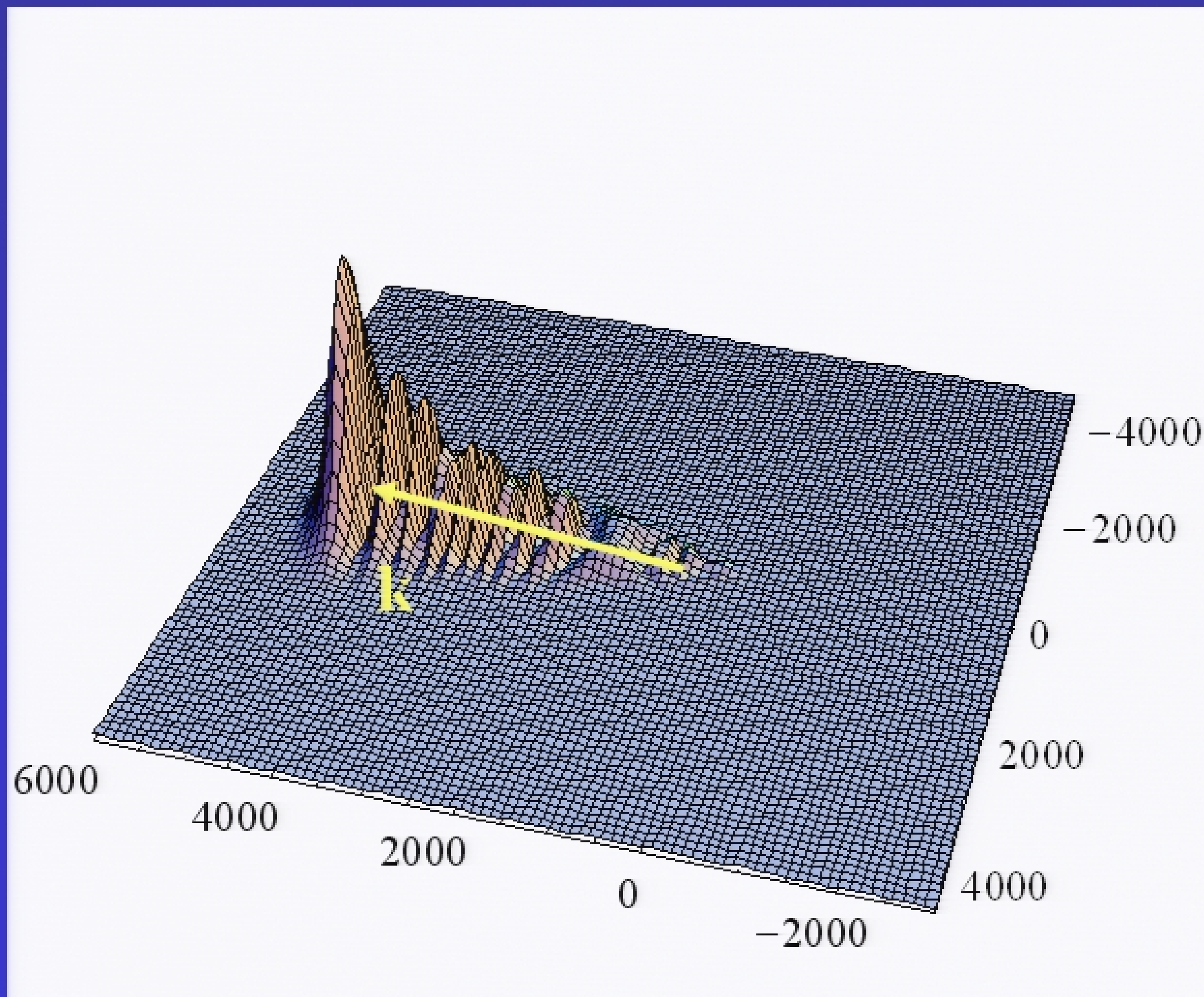

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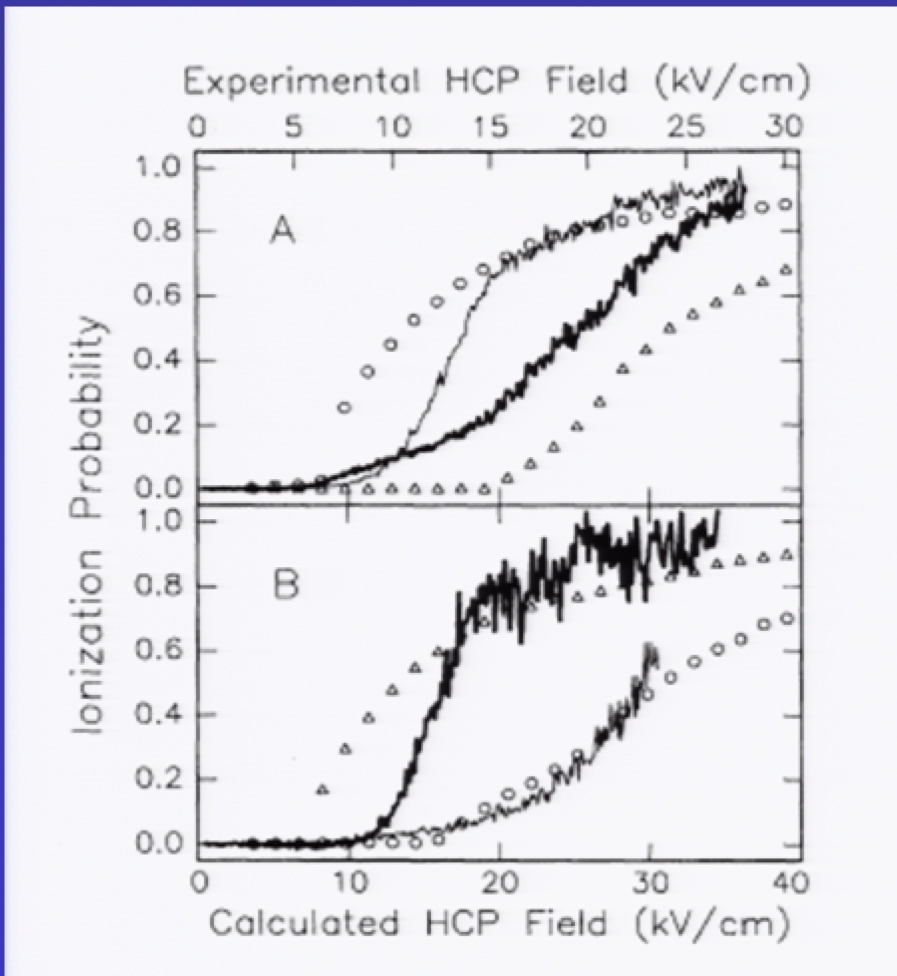

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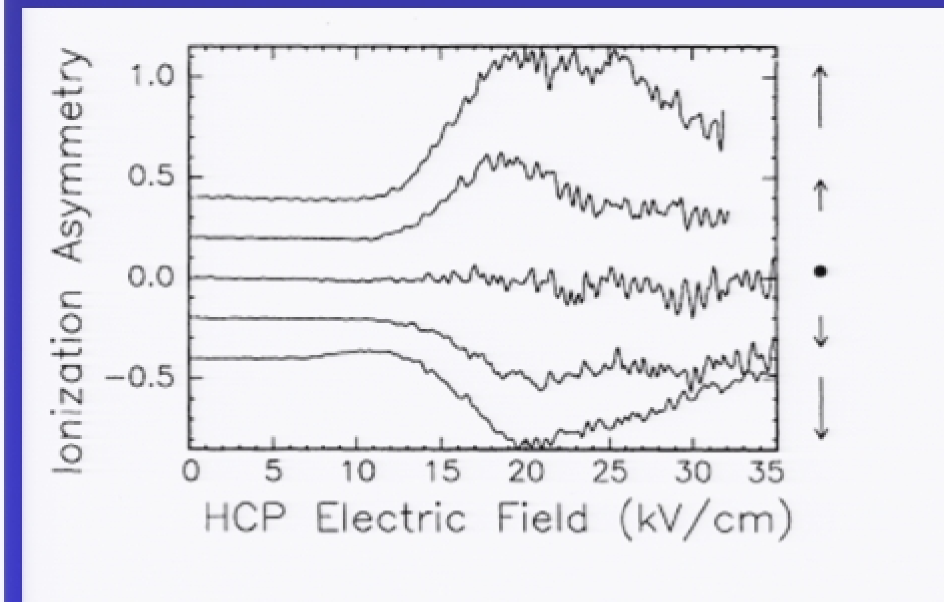

Summary

- For transmission of one direction, LRL vector is better than angular momentum.

- Elliptic states are not optimal for transmission of one axis, but are nearly optimal for frames.

- They are practical.

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Summary

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- Spontaneous decay:

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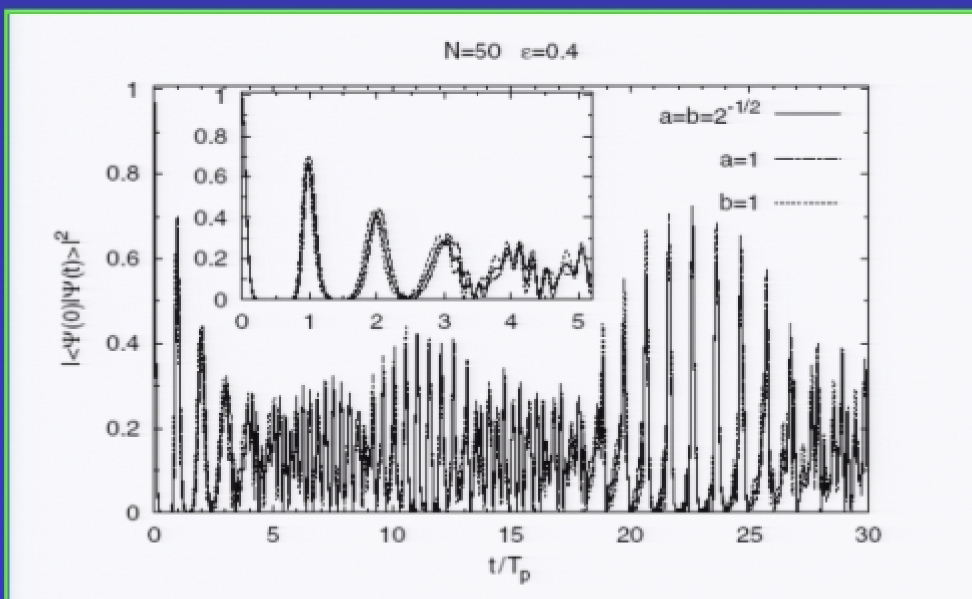
$$E_{nlj} = E - \frac{Z^4\alpha^2}{2n^3(l+s+1/2)} \qquad j = l + s$$

$$T_p = \frac{2\pi}{\left\langle \frac{dE_{nlj}}{dl} \right\rangle} \qquad T_p = \frac{4\pi n^3\left[(n-1)\cos\zeta\right]^2}{Z^4\alpha^2}$$

P. Rozmej et al, J. Phys. A **35**, 7803 (2002)



Outline | Slides

magnetic field. J.C. Day et al, PRL. 72 (1994

- Relativistic effects:
- Energy depends on l, causes precession of the elliptic state. P. Rozmej et al, J. Phys A. 35 (2002)

31

Characteristic Time Scales 32

- For Z=1 :
- Spontaneous decay:

Probing the orientation of Rydberg states by an ionization pulse 33

Summary 34

- For transmission of one direction, LRL vector is better than angular momentum.
- Elliptic states are not optimal for transmission of one axis, but are nearly optimal for frames.
- They are practical.

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$$E_{nlj} = E - \frac{Z^4\alpha^2}{2n^3(l+s+1/2)} \qquad j = l + s$$

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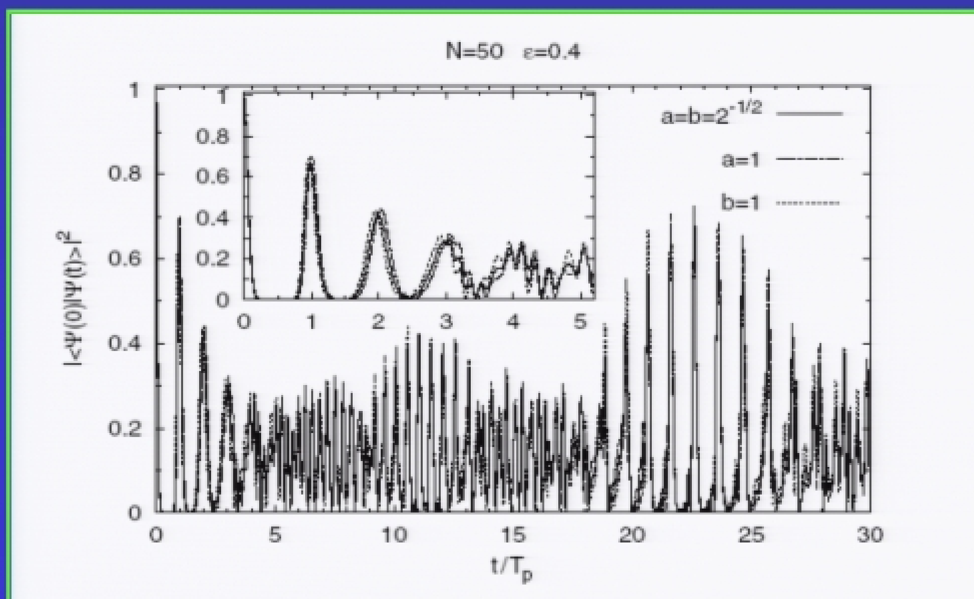

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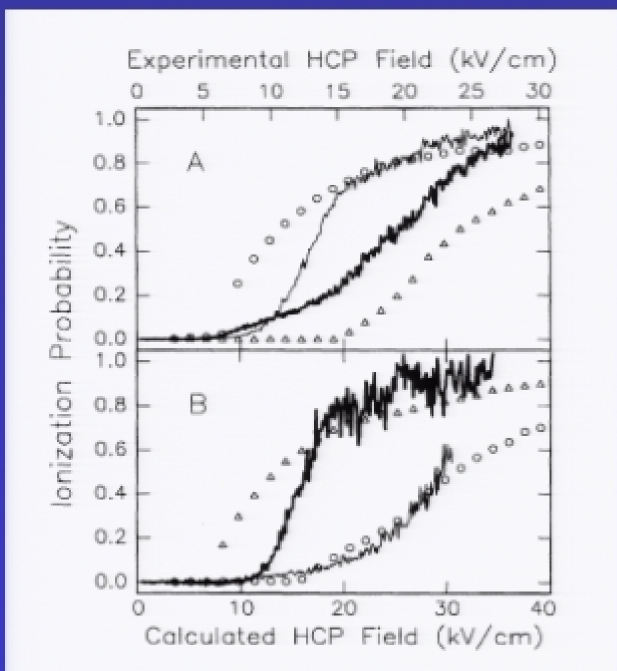
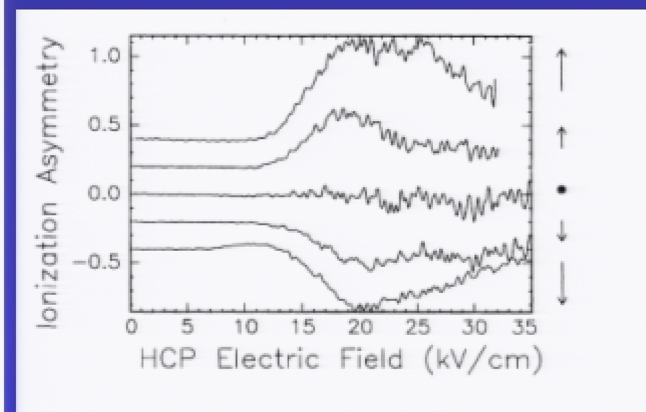
Probing the orientation of Rydberg states by an ionization pulse



Jones et al, **PRA 51 2687 (1995)**



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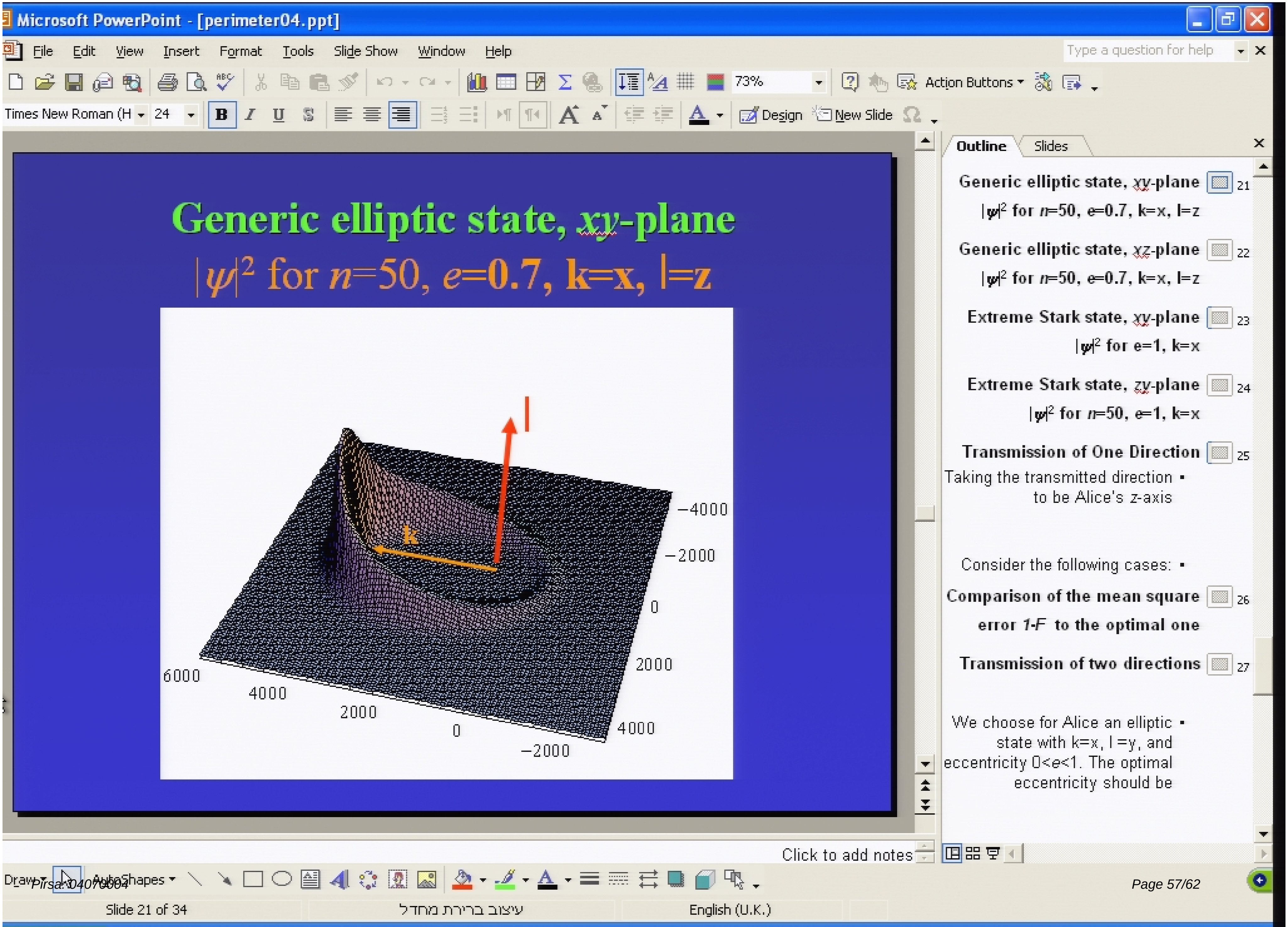
Microsoft PowerPoint - [perimeter04.ppt]
Generic elliptic state, xy-plane
|ψ|² for n=50, e=0.7, k=x, l=z
l
k
−4000
−2000
0
2000
4000
6000
4000
2000
0
−2000
Outline
Slides
Generic elliptic state, xy-plane
|ψ|² for n=50, e=0.7, k=x, l=z
Generic elliptic state, xz-plane
|ψ|² for n=50, e=0.7, k=x, l=z
Extreme Stark state, xy-plane
|ψ|² for e=1, k=x
Extreme Stark state, zy-plane
|ψ|² for n=50, e=1, k=x
Transmission of One Direction
Taking the transmitted direction to be Alice's z-axis
Consider the following cases:
Comparison of the mean square error 1-F to the optimal one
Transmission of two directions
We choose for Alice an elliptic state with k=x, l=y, and eccentricity 0<e<1. The optimal eccentricity should be
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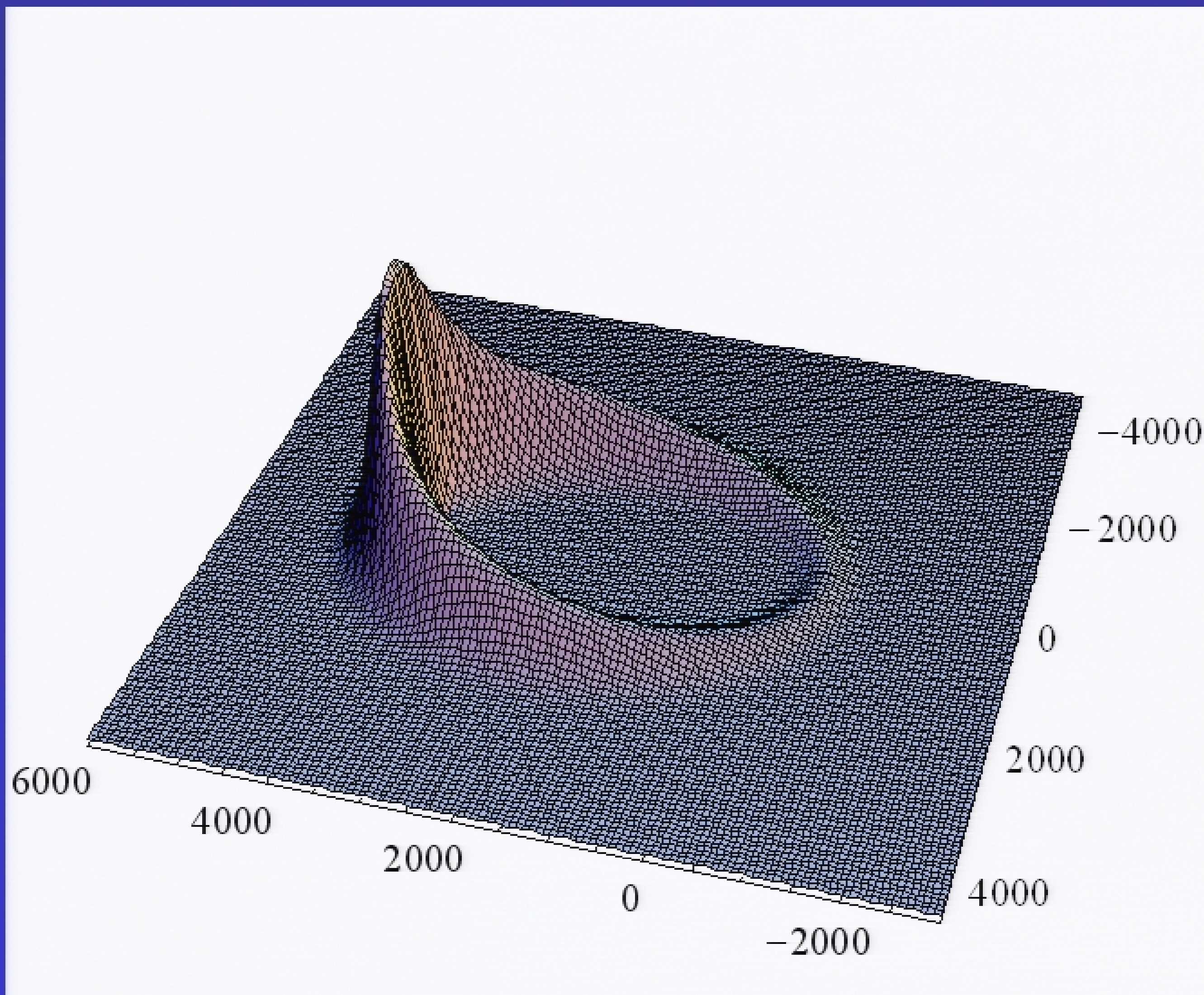
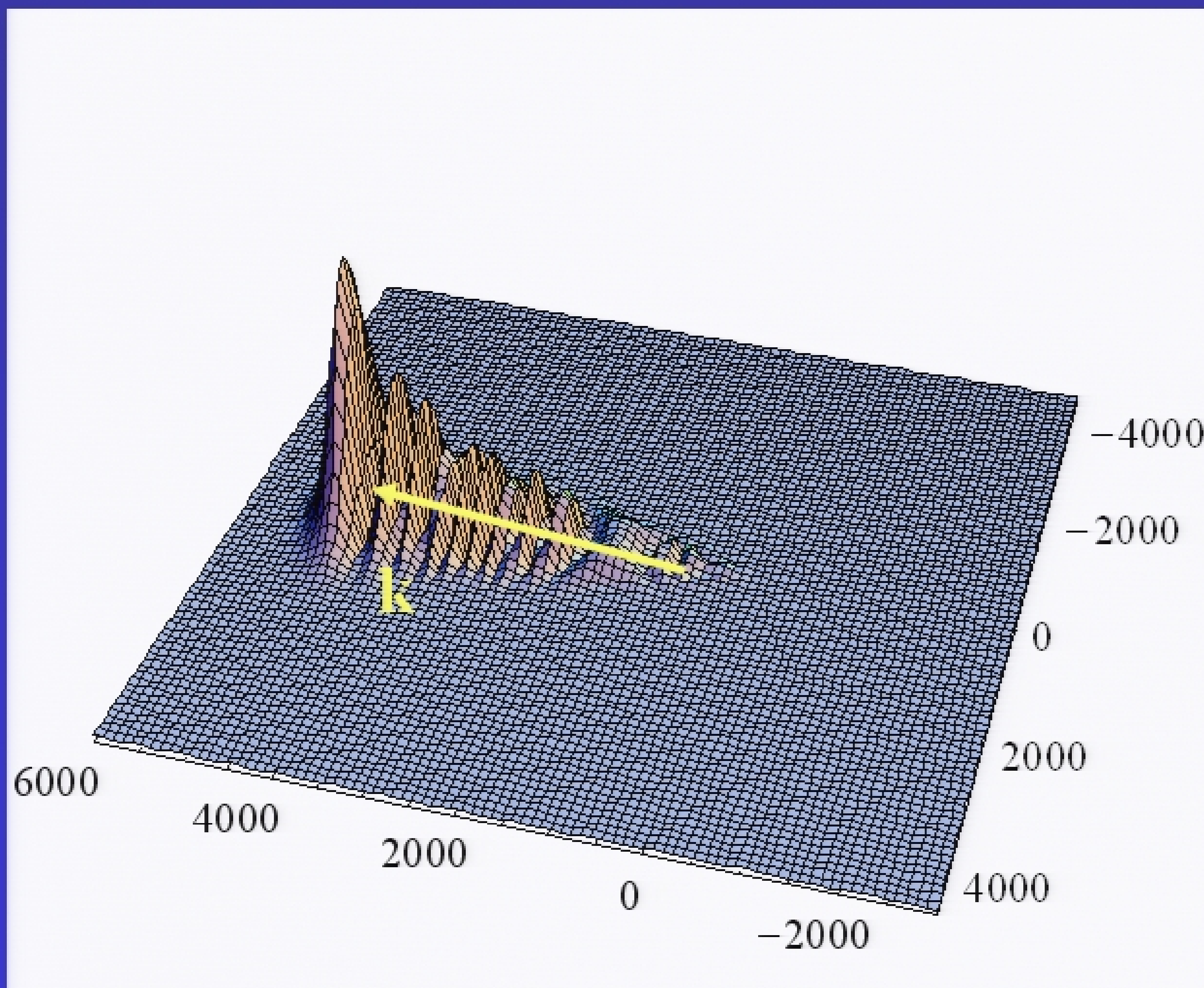
Generic elliptic state, *xy*-plane

$|\psi|^2$ for n=50, e=**0.7**, **k=x**, **l=z**



Extreme Stark state, *xy*-plane

$|\psi|^2$ for e=1, k=x



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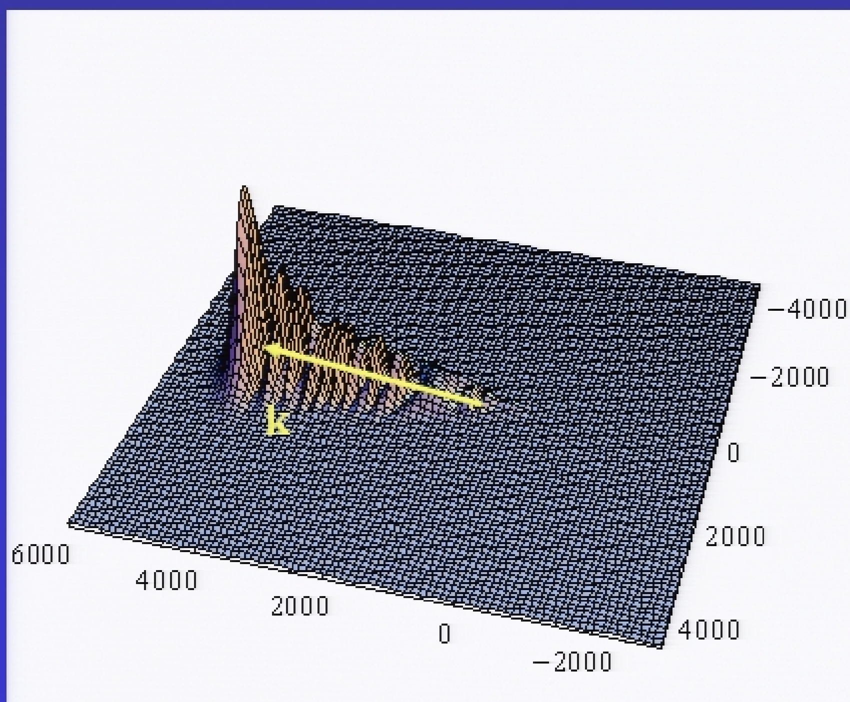
Extreme Stark state, *xy*-plane

$|\psi|^2$ for e=1, k=x



Generic elliptic state, xy-plane
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Generic elliptic state, xz-plane
$|\psi|^2$ for n=50, e=0.7, k=x, l=z

Extreme Stark state, xy-plane
$|\psi|^2$ for e=1, k=x

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SSH Secure File Transfer Client
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Adobe Reader 6.0
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GSview
Launch Inter...
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טיול פסח